

Paleocene-Eocene Thermal Maximum environmental change in the New Jersey Coastal Plain: benthic foraminiferal biotic events

STASSEN Peter¹, THOMAS Ellen^{2,3} and SPEIJER Robert, P.¹

¹Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, B-3001, Leuven, Belgium (Peter.Stassen@ees.kuleuven.be, Robert.Speijer@ees.kuleuven.be).

²Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, Connecticut 06520-8109, USA (ellen.thomas@yale.edu).

³Department of Earth and Environmental Sciences, 265 Church Street, Wesleyan University, Middletown, Connecticut 06459, USA (ethomas@wesleyan.edu).

ABSTRACT

The environmental impact of the Paleocene-Eocene Thermal Maximum (PETM) has been intensively studied in the New Jersey Coastal Plain, but the benthic foraminiferal response, reflecting bottom water conditions, has not been documented at high resolution. We use benthic foraminiferal data across the Paleocene-Eocene boundary in cores from Wilson Lake (WL) and Bass River (BR) to recognize 5 foraminiferal associations (based on species clusters). Their varying abundances allow the identification of a stratigraphic succession of 8 distinct biofacies across the studied interval. Uppermost Paleocene biofacies 1 corresponds to the glauconitic sands of the Vincentown Formation and contains rare, small planktic foraminifera and a diverse benthic fauna. Sediments accumulated slowly in a sufficiently oxygenated, outer neritic setting (depth: 100-110 m at WL, 140-150 m at BR) under fairly oligotrophic conditions. The embayment was storm-dominated and influenced by strong currents, inhibiting deposition of suspended fine particles (e.g., planktic foraminifera, clay) and enhancing re-suspension. No significant pre-PETM environmental changes are detected in the benthic foraminiferal assemblages.

Deposition of the fine-grained silty clays of the Marlboro Clay started at the onset of the PETM, with transitional lithology present at Wilson Lake. *Gavelinella beccariiformis*, common at deep shelfal to bathyal-abyssal depths, is the only taxon to become extinct at this level. Water depth increased during the PETM to a maximum of 130-150 m at WL. Planktic foraminifera increased strongly in abundance, while the benthic foraminiferal assemblage changed to a more opportunistic, less diverse assemblage dominated by stress-tolerant taxa (*Tappanina selmensis*, *Pulsiphonina prima* and *Anomalinoides acutus*, biofacies 2). Increased riverine influence may have reduced vertical mixing, initiating stratification of the water column, and establishment of a continuously dysoxic mud belt. Benthic diversity then gradually increased, indicating environmental recovery (biofacies 3 and 4; 40-95 kyr post PETM-onset). Riverine influence probably became more variable, generating peak abundances of specialized taxa in a mud belt system with increased accumulation rates. The latest PETM biofacies 5 (>95 kyr post-onset) contains a poorly diverse *Bulimina callahani* assemblage, indicative of reoxygenated, but still eutrophic bottom water conditions, with renewed vertical mixing. The lower Eocene glauconitic sandy clays of the Manasquan Formation contain an outer neritic benthic fauna (biofacies 6 to 8, depth: 100-135 m at WL) indicative of persistent high primary production, with return of more vigorous currents. Higher abundances of buliminids may have been triggered by upwelling along frontal zones. Our environmental interpretations indicate relatively stable benthic foraminiferal ecosystems at persistently outer neritic water depths (100-150 m), despite distinct temporary

changes during the PETM, including eustatic sea-level rise of up to ~30 m, and widespread establishment of dysoxic conditions.

* Corresponding author

Dr. Peter Stassen

Biogeology Research Group, Department of Earth and Environmental Sciences, KU Leuven
Celestijnenlaan 200E, B-3001 Leuven, Belgium

Tel: +32 (0)16 32 64 52

Fax: + 32 (0)16 32 29 80

Peter.Stassen@ees.kuleuven.be

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1 INTRODUCTION

The early Paleogene was a climatically dynamic period with relatively rapid global warming events, called hyperthermals, superimposed on a warm background greenhouse climate. The best known and most extreme hyperthermal is the Paleocene-Eocene Thermal Maximum (PETM; Kennett and Stott, 1991; Thomas and Shackleton, 1996; Zachos et al., 2008), characterized by worldwide 5-8 °C warming of Earth's surface as well as the deep oceans (McInerney and Wing, 2011; Dunkley Jones et al., 2013). Sea-surface temperature records of the New Jersey shelf indicate up to 8 °C local warming during the early stages of the PETM, with peak temperatures in excess of 33 °C (Zachos et al., 2006). The PETM is also marked by a globally recorded negative carbon isotope excursion (CIE; Thomas and Shackleton, 1996; McInerney and Wing, 2011), which base marks the Paleocene-Eocene (P-E) boundary (Dupuis et al., 2003; Aubry et al., 2007).

Although the ultimate cause and trigger of the CIE are under debate, the thermal liberation of methane hydrates along continental margins is a plausible way to rapidly inject large amounts of ¹³C-depleted carbon into the ocean-atmosphere system (e.g., Dickens et al., 1997; Dickens, 2011). Other hypotheses include a rapid release of thermogenic methane from volcanic basins (Svensen et al., 2004), burning of peat deposits or oxidation of organic matter following desiccation of inland seas (Kurtz et al., 2003; Higgins and Schrag, 2006), thawing Antarctic permafrost (DeConto et al., 2012) and comet impact (Kent et al., 2003; Wright and Schaller, 2013).

This abrupt warming was coupled with major evolutionary changes in the marine biosphere (Speijer et al., 2012), including extinction of common, cosmopolitan deep-sea benthic foraminifera (e.g., Tjalsma and Lohmann, 1983; Thomas, 1989, 1998), rapid evolutionary turnover in planktic communities (e.g., Kelly et al., 1996; Bralower, 2002; Gibbs et al., 2006a; 2006b; Schneider et al., 2013), an acme of the dinoflagellate *Apectodinium* at middle and high latitudes (e.g., Crouch et al., 2001; Sluijs et al., 2007a), and reorganization of carbonate platform communities with a turnover of larger foraminifera (e.g., Scheibner et al., 2005; Scheibner and Speijer, 2008). Compared to the deep-sea foraminiferal crisis, the evolutionary effect of the

PETM on benthic foraminiferal communities was apparently less severe in shelf settings (e.g., Speijer et al., 1996), although shelf benthic foraminiferal communities has not yet been extensively documented worldwide.

The New Jersey Wilson Lake (WL) and Bass River (BR) drill sites in the Atlantic Coastal Plain of North America contain upper Paleocene - lower Eocene shelf sequences with a well-documented PETM (Figs. 1 and 2). These sediments include kaolinite-rich, silty clays deposited during the PETM, and contain biogenic magnetic particles (Kopp et al., 2007; Lippert and Zachos, 2007; Schumann et al., 2008). Their accumulation and preservation implies expansion of the suboxic zone within the sediment (Dickens, 2008), possibly linked to the establishment of a tropical river-dominated shelf (Kopp et al., 2009). High-resolution records are available for stable isotopes (Cramer et al., 1999; Zachos et al., 2006, 2007; Sluijs et al., 2007b; John et al., 2008; Stassen et al., 2012b), calcareous nannoplankton (Gibbs et al., 2006a; 2006b) and organic dinocyst assemblages (Sluijs et al., 2007b; Sluijs and Brinkhuis, 2009). A bloom of the heterotrophic dinocyst *Apectodinium* preceded the PETM by 4-5 to 40-45 kyr, continuing in the early stages of global warming (Sluijs et al., 2007b; Stassen et al., 2012c). PETM dinocyst distribution indicates varying riverine influence across the shelf, causing eutrophication and potentially salinity-driven stratification (Sluijs and Brinkhuis, 2009). In contrast, highly diverse nannoplankton assemblages indicate stable, mesotrophic surface water conditions with limited salinity changes (Gibbs et al., 2006b).

Paleoenvironmental reconstructions of sea-floor conditions based on benthic foraminifera have been performed at low resolution only (e.g., Gibson et al., 1993; Gibson and Bybell, 1994; Harris et al., 2010). Benthic biota provide essential information on sea-level fluctuation, bottom water oxygenation and organic fluxes to the sea floor at the time of deposition. We present high-resolution benthic foraminiferal distribution patterns for the two best-studied New Jersey Coastal Plain sites (Wilson Lake and Bass River), aiming to document the response of shallow marine benthic foraminifera to greenhouse warming during the PETM, to detect regional biotic patterns, and to decipher environmental mechanisms controlling benthic ecosystems of this continental shelf, using the stratigraphic framework of Stassen et al. (2012b).

2 MATERIAL AND METHODS

Samples were obtained from cores at Wilson Lake (drilled by the United States Geological Survey (USGS), latitude N39°39'21", longitude W75°02'31") and Bass River (drilled by Ocean Drilling Program (ODP) Leg 174X, latitude N39°36'42", longitude W74°26'12"). Bass River is approximately 35 km down-dip along the basin gradient (1:1000, Olsson and Wise, 1987), thus in waters about 35 m deeper than at Wilson Lake. Sample spacing was 30 cm for most of the studied interval, up to 5-10 cm around the P-E boundary. Published calcareous nannofossil (Aubry et al., 2000; Gibbs et al., 2006a, 2006b; Bybell, pers. comm. 2013) and stable isotope records (Cramer et al., 1999; Zachos et al., 2006; John et al., 2008) provide the main stratigraphic framework (Fig. 2), supported by a sequence of bioevents (Sluijs and Brinkhuis, 2009; Stassen et al., 2012b, 2012c). Unconformities are recognized by sharp lithologic changes and nannoplankton biostratigraphy (Cramer et al., 1999; Gibbs et al., 2006a). We note a previously unreported unconformity at Wilson Lake at 93.15 m, coinciding with a major change in lithology and biota.

Preservation of calcareous nannofossils is good to excellent, and we used the biozonation by Aubry (1996; 1999). The lowest occurrence of *Discoaster araneus* separates NP9a and NP9b. Zone NP10 is subdivided using the ranges of *Tribrachiatius digitalis* (NP10b) and *Tribrachiatius*

contortus (NP10d) and the partial range of *Tribrachiatus bramlettei* (NP10a and NP10c). These subdivisions are commonly applied in shelf settings (e.g., Dupuis et al., 2003), yet deep-sea records show that the lowest occurrence of *T. contortus* may precede the lowest occurrence of *T. digitalis*, so that this subdivision may not be globally valid (e.g., Agnini et al., 2007). Here Subzones NP10b, 10c and 10d are combined into zone NP10b-d, its base being defined by the lowest occurrence of either *T. digitalis* or *T. contortus*, its top by the highest occurrence of *T. contortus* (Fig. 2).

About 20-40 g sediment was dried and washed over a 63 μm sieve until complete disaggregation. A representative split for quantitative analysis (approximately 250-300 benthic specimens) was obtained from the >63 μm fraction using a microsplitter. From these splits all benthic specimens were picked, identified, counted and permanently stored in Plummer slides (KU Leuven). In order to concentrate the calcareous foraminiferal tests in samples with abundant quartz or glauconite grains, a flotation technique (zinc chloride solution) was applied, which slightly reduces absolute abundances, but relative abundances are unaffected (Semensatto and Dias-Brito, 2007). Visual inspection of the heavy fraction (quartz and glauconite grains) revealed only broken chambers of large nodosariids.

We determined foraminiferal numbers (individuals >63 μm per gram sediment), the planktic-benthic ratio (%P), the proportions of epi- and endobenthic morphotypes, faunal diversity (Fisher alpha: $F(\alpha)$ and Shannon: $H(s)$ indices), benthic foraminiferal abundances and paleoecologic preferences of the most common taxa. The terms coastal, inner neritic, middle neritic and outer neritic correspond respectively to 0-30 m, 30-50 m, 50-100 m, 100-200 m paleodepth. Benthic foraminifera were mostly identified to species level, but in some cases to genus level, e.g., *Pullenia* spp., *Lenticulina* spp. and other nodosariids. Diversity indices were calculated using initial data sets containing all counted benthic species (PAST-software, Hammer et al., 2001). Relative benthic foraminiferal abundances are expressed as the proportion (percentage) of a species in the entire benthic foraminiferal assemblage. Only the most common taxa (>2.5% in at least one sample) are displayed in the figures, with remaining species placed in the 'rest group', which also includes indeterminable benthic taxa. Cluster analysis and detrended correspondence analysis (DCA) was performed to analyze the relative abundance data of Wilson Lake and Bass River statistically (data set with >2.5%; PAST-software; Hammer et al., 2001). We used cluster analysis to group benthic foraminiferal taxa in species associations, supposedly containing taxa with closely related paleoecologic preferences. A stratigraphic succession of biofacies is based upon varying abundances of these benthic foraminiferal associations.

Benthic foraminifera are employed widely as a tool to reconstruct paleoenvironments and benthic foraminiferal shelf species are directly affected by environmental parameters that tend to vary proportionally with depth. Food availability and oxygen are the main factors controlling the density and microhabitat distribution of benthic foraminifera (e.g., Jorissen et al., 1995, 2007; van der Zwaan et al., 1999). In general, organic flux is important, but it becomes subordinate in food-rich environments when oxygen becomes strongly limiting. High proportions of epibenthic morphotypes are generally indicative of well-ventilated, relatively oligotrophic marine conditions (e.g., Corliss and Chen, 1988; Corliss, 1991; Jorissen et al., 1995). Taxa with an endobenthic morphology become more prominent as the organic flux to the seafloor increases (mesotrophic to eutrophic conditions) and show relative population increases under low-oxygen bottom water conditions (Jorissen, 1999; Jorissen et al., 2007). Low-oxygen assemblages commonly have low diversity and are dominated by small, thin-walled benthic taxa (Boltovskoy et al., 1991; Bernhard and Sen Gupta, 1999), which might better survive under such conditions (e.g., Ernst et al., 2005).

The abundance of planktic foraminifera generally increases with distance from the coast and water depth, and is highest in open ocean environments (e.g., van der Zwaan et al., 1990), so that the %P has been proposed as an indicator of water depth. Planktic abundance reflects the vertical niche availability (thermocline structure) and niche stability throughout the year. However, quantitative calibration is difficult and varies regionally because %P may also be influenced by bottom water conditions (van Hinsbergen et al., 2005), productivity (Berger and Diester-Haass, 1988; Olsson et al., 1997), surface salinity and turbulence, and post-mortem taphonomic change. We assigned paleodepth preferences to our foraminiferal associations (see supplementary data) and our depth estimates for each biofacies are based on the relative cumulative abundances of each species association. $Depth_{trend} = 1/n_{total} \sum (n_i * (depth_{min, i} + depth_{max, i})/2)$, in which n_i represents the percentage of association 'i', minimal and maximal depth of association 'i' refer to the upper and lower limits of preferred water depth. Two calculations are performed, including or excluding species association IIa (indicated by *), because this group has reported peak abundances at radically differing water depths, suggesting large environmental tolerance.

3 GEOLOGICAL SETTING AND STRATIGRAPHY

The central Atlantic coast of North America is a passive continental margin where Cenozoic sediments were deposited in embayments separated by elevated areas, related to flexures in the underlying basement (e.g., Gibson et al., 1993). The New Jersey Coastal Plain (NJCP) is situated in the northern part of the Salisbury embayment, and contains expanded marine records of P-E boundary sediments (Gibson et al., 1993; Gibson and Bybell, 1994; Cramer et al., 1999). The present-day Fall Line marks the outcrop boundary between deformed basement rocks and onlapping undeformed Mesozoic and Cenozoic sediments (Fig. 1). Marine sediments were deposited more westward, to an unknown extent due to erosion (Gibson and Bybell, 1994).

The upper Paleocene (NP9a) Vincentown Formation (Fm.) consists of glauconitic quartz sands, and shifts downdip to more fine-grained glauconitic quartz-rich silts and clays (Olsson and Wise, 1987). The lower Eocene Manasquan Fm. (top NP10a to base NP11) consists commonly of extensively burrowed calcareous clays to silts or very fine sands, with some glauconitic beds (Olsson and Wise, 1987), and is stratigraphically more complete at Wilson Lake (Stassen et al., 2012b). The sediments accumulated slowly on a sediment-starved, siliciclastic shelf and regional unconformities are present (Olsson and Wise, 1987; Browning et al., 2008).

An interval of silty clay is intercalated in these glauconitic sediments (thickness WL: 13.5 m and BR: 10.5 m; Fig. 2), initially referred to as the 'unnamed unit' (Olsson and Wise, 1987), or attributed either to the Vincentown or the Manasquan Fm. (e.g., Gibson et al., 1993; John et al., 2008). This sequence is now assigned to the PETM, based on the recognition of the CIE, high proxy-derived temperatures, and distinctive nannoplankton marker taxa (Cramer et al., 1999; Gibbs et al., 2006a; Zachos et al., 2006). At Bass River, the CIE onset is at 357.3 m below surface. The onset is not as clear at Wilson Lake because of a carbonate-free level, but recognized around 110 m below surface in the $\delta^{13}C_{org}$ (dinocyst) record. The upper boundary of the CIE interval is truncated at both sites, unconformably overlain by glauconitic clays to clayey silts (unconformity BR 347.05 m and WL 96.32 m). The New Jersey silty clays are in a similar stratigraphic position as the Marlboro Clay in the southern Salisbury Embayment (Gibson and Bybell, 1994; Kopp et al., 2009). The basal Eocene clays in the NJCP are therefore also attributed to the Marlboro Clay, which has been described as deposited in a shelf-wide mud belt on a river-

dominated shelf, with high detrital input (Kopp et al., 2009; Stassen et al., 2012b), in contrast with the sediment-starved glauconitic depositional regimes which are more common in the basin.

4 RESULTS

4.1. General

The foraminiferal assemblage in the uppermost Paleocene glauconitic sands of the Vincentown Fm. in both cores consists of sparse, small planktic foraminifera and a diverse benthic foraminiferal fauna (Figs. 3 and 4), with large trochospiral epibenthic (e.g., *Gavelinella beccariiiformis*, *Cibicidoides alleni*) as well as common, fairly small triserial endobenthic components (e.g., *Bulimina virginiana*, *Bulimina hornerstownensis*). Foraminifera at both sites are fairly well-preserved, but have a whitish ('frosty') appearance and commonly are broken or abraded. The onset of the CIE occurs at the transition from glauconitic sands to silty clays (Fig. 2). A transitional biofacies, composed of both Paleocene and Eocene faunal components, occurs at Wilson Lake within a gradual lithologic transition, which was not recognized at Bass River (Figs. 5 and 6). Planktic foraminiferal abundance rapidly increases from this level onwards.

In the PETM interval, the benthic foraminiferal fauna is less diverse, and dominated by *Pulsiphonina prima*, *Tappanina selmensis* and *Anomalinoides acutus*. In general, specimens are excellently preserved (translucent) and not abraded. Foraminiferal diversity gradually increases upwards within the PETM interval, with high abundances of *Pseudouvigerina wilcoxensis* and *Spiroplectinella laevis*, and distinct higher abundances of *Bulimina callahani* in the upper meters of the clayey strata at Bass River. An unconformity cuts into the upper part of the PETM at both sites (Stassen et al., 2012b). The overlying glauconitic sandy clays of the Manasquan Fm. at Wilson Lake contain relatively well-preserved foraminifera with only minor abrasion, and the fauna is most comparable to the uppermost Paleocene one, but richer in planktic foraminifera.

4.2 Foraminiferal species associations and biofacies

Benthic foraminiferal taxa are grouped in 5 species associations (I to V in Fig. 7) using cluster analysis, with the associations supposedly containing taxa with closely related paleoecologic preferences. Species association III, composed of *Fursenkoina wilcoxensis* and *Bulimina ovata*, is not discussed in detail due to the low abundances of these taxa. Representative taxa for all species associations are illustrated: Ia and Ib (plate 1), IIa, IIb, III and IV (plate 2), and V (plate 3). The sedimentary sequence is subdivided in 8 distinct biofacies with 1 transitional biofacies, based on the varying proportions of the species associations and lithologic characteristics (Tables 1 and 2). The base of biofacies 3 is placed at a major increase in sedimentation rates (Stassen et al., 2012b). The biofacies subdivision forms the framework of the paleoenvironmental interpretation, supported by detrended correspondence analysis (Fig. 8; see 4.3). The correlations of the biofacies between the studied sites are considered isochronous, based on the tie points in the carbon isotope excursion, nannoplankton biostratigraphy and site-to-site correlation of dinocysts events (Stassen et al., 2012b). Foraminiferal distributions at the deeper Bass River and shallower Wilson Lake sites are thus stratigraphically consistent through the studied sections, indicating that environmental changes at the onset of the PETM occurred on a larger regional scale, rather than migrating up- or downdip with changes in sea level (Stassen et al., 2012b). Stratigraphically, biofacies 1 was deposited during the latest Paleocene, biofacies 2 and 3 during the peak warming of the PETM (CIE 'core'), and biofacies 4 to 5 during the CIE

recovery phase (Fig. 2, Stassen et al., 2012b). Post-PETM, lower Eocene biofacies 6 to 8 are intercalated between unconformities.

Uppermost Paleocene biofacies 1 occurs at Wilson Lake (111.74-109.99 m), in glauconitic (clayey) sands between barren intervals, and is characterized by the lowest foraminiferal numbers and %P of all biofacies. The benthic fauna is moderately diverse, with a strong dominance of association Ia species, mainly *B. virginiana*. At Bass River (362.86-357.29 m), this biofacies occurs in glauconitic silty micaceous clay and foraminifera are more common than at Wilson Lake. The assemblage is more diverse and mainly composed of association Ib species, such as *B. hornerstownensis*, *G. beccariiiformis* and *Paralabamina lunata*.

As noted by Gibson et al. (1993), the transitional biofacies at the CIE onset is more diverse, containing characteristic elements of both Paleocene and PETM biota. It is restricted to thin intervals at Wilson Lake (109.50-109.27 m, directly above the barren interval) and Bass River (357.29-357.18 m). The lithology is transitional, with sediments becoming more fine-grained upwards (clayey silt), while the glauconite content decreases. *Gavelinella beccariiiformis* has its highest occurrence below this level. Benthic foraminifera are less common, yet planktic foraminifera become more abundant than in biofacies 1. *Bulimina virginiana* (WL) and *B. hornerstownensis* (BR) remain common, and *A. acutus* and *P. prima* (association IIa) become abundant at both sites. At Wilson Lake, isotope records of *C. alleni* (association Ia) and *A. acutus* (association IIa) both show CIE values, but at Bass River isotope values are a mixture of Paleocene and CIE values (Fig. 2) indicating bioturbation and/or reworking (Cramer et al., 1999; Stassen et al., 2012b).

Biofacies 2 is present in dark gray silty clay without glauconite (WL 109.27-103.65 m; BR 357.18-356.30 m), deposited during peak warming of the PETM. Foraminiferal numbers and %P increase significantly compared to the transitional biofacies, reaching the highest mean values of all biofacies (Figs. 3 and 4). Extremely high foraminiferal numbers occur in the basal PETM at Bass River, which is condensed relative to Wilson Lake (Stassen et al., 2012b, 2012c). The benthic foraminiferal assemblage is less diverse than in the transitional biofacies, with a dominance of association IIa species (*T. selmensis*, *A. acutus* and *P. prima*).

The succeeding biofacies 3 is present in dark silty clays without glauconite and is the uppermost biofacies represented at both sites (WL 103.65-96.32 m, truncated by an unconformity; BR 356.30-352.82 m). At Wilson Lake, %P and foraminiferal numbers remain high, although %P decreases upwards, whereas diversity remains stable (Fig. 3). Species of association IIa (*A. acutus* and *P. prima*, no *T. selmensis*) are less dominant, and association IIb taxa reach maximum abundances (e.g., *P. wilcoxensis*). The patterns are similar at Bass River, but there diversity gradually increases upwards. *Anomalinoidea acutus*, *P. prima* and *T. selmensis* (association IIa), and *B. hornerstownensis* and *P. lunata* (association Ib) are major faunal components. Species of association IIb are more evenly distributed, because *P. wilcoxensis* is less dominant.

Biofacies 4 and 5 represent the PETM recovery phase, both present at Bass River only, in dark clays mostly without glauconite. Biofacies 4 (initial CIE recovery phase, Fig. 2) occurs at 352.82-348.86 m. Foraminiferal numbers and %P remain high, but gradually decrease upwards. This biofacies is the most diverse, consisting of a mixture of all foraminiferal species associations, with *P. prima* (association IIa) and *P. lunata* (association Ib) being most common. Biofacies 5 (BR 348.86-347.05 m), is truncated at the top by an unconformity and rare glauconite grains at the top (BR 347.52 m) probably indicate downward bioturbation. Foraminiferal numbers are very low, with reduced %P and low carbonate content. The assemblage is poorly diverse and strongly dominated by *B. callahani* (association V).

Lower Eocene biofacies 6 to 8 are intercalated between unconformities at Wilson Lake (Fig. 2). The sediments containing biofacies 6 (WL 96.32-94.79 m) consist of glauconitic, clayey silts with high benthic foraminiferal numbers and low %P relative to the underlying PETM biofacies. The diverse benthic foraminiferal assemblage is mainly composed of association V species, while taxa of association IIa (*A. acutus* and *P. prima*) are consistently present, but association I species are rare. Biofacies 7 (WL 94.79-93.15 m) occurs at Wilson Lake in glauconite-rich clayey silt. Benthic foraminiferal numbers increase significantly and the poorly diverse assemblage is mainly composed *B. virginiana* (association Ia). The dominant lithology within biofacies 8 (WL 93.15-90.53 m) is glauconitic clayey silt with common fine quartz grains. The assemblage is moderately diverse and resembles biofacies 1, although *A. acutus* and *P. prima* are continuously present.

4.3 Detrended correspondence analysis (DCA)

The biofacies with hypothetical derived environmental conditions are visualized in a bivariate plot of sample scores on the first and second DCA axes (Fig. 8A), the ordinations of the most common taxa (>5% in at least one sample, 34 taxa in total) are shown in Fig. 8B, and the paleoecologic interpretation of the main species associations in Fig. 8C. Axis 1 (explaining 20.8% of the variance) separates PETM biofacies 2 and 3 from all others. Axis 2 (explaining 17.7% of the variance) mainly separates PETM biofacies 5 from all others, particularly Paleocene Bass River biofacies 1.

Most large epibenthic morphotypes (e.g., *Cibicidoides succedens*, *C. alleni* and *G. beccariiiformis*) have more positive scores on axis 1 than most endobenthic morphotypes (Fig. 8B). *Gavelinella beccariiiformis*, which is characteristic for oxic, oligotrophic environments (Widmark and Speijer, 1997; Clemmensen and Thomsen, 2005), plots very high on axis 1, low on axis 2, whereas most buliminids, with the exception of *B. hornerstownensis*, plot more positively on axis 2. *Paralabamina lunata* is a common species in mesotrophic, moderately to well-ventilated shelf environments in the North Sea and Egyptian basins (Clemmensen and Thomsen, 2005; Ernst et al., 2006), extending into overall oligotrophic deep-sea environments (Thomas, 1998). This species has intermediate values on axis 1 and relatively low values on axis 2. *Anomalinoides zitteli* and *B. callahani* plot high on both axes 1 and 2. These species have generally been reported to occupy dysoxic to oxic environments with high organic flux (e.g., Dababiya section in Egypt, Ernst et al., 2006). *Tappanina selmensis*, *A. acutus* and *P. prima* have low values on axis 1 and intermediate values on axis 2. Olsson and Wise (1987) noted that these stress-tolerant taxa are common components in small-sized, low-diversity faunas in the NJCP, and are regarded as indicators of hypoxic environments. We conclude that the DCA axes represent changes in bottom water conditions, linked to bottom water oxygenation (axis 1) and organic flux to the sea floor (axis 2). Paleodepth appears less important, because taxa associated with an outer shelf living habitat (Fig. 9 and supplementary data) have both high and low scores on both axes (e.g., *B. callahani*: association V, *G. beccariiiformis*: association Ib, *A. acutus*: association IIa).

Distinct paleoecologic affinities are thus attributed to these statistically identified foraminiferal associations (Fig. 8C). Many benthic foraminiferal taxa (e.g., *C. alleni*, *C. succedens*, *A. acutus*, *P. prima* ...) are part of the globally recognized, Midway-type shelf fauna (Berggren and Aubert, 1975), although some common taxa may be restricted to the Salisbury embayment (e.g., *B. virginiana* and *B. hornerstownensis*). These interpretations may be extended to other open shelf settings in the Salisbury embayment, but extrapolation to more remote shelf

margins is more problematic. Some of these foraminiferal associations are recognizable in other shelf settings despite differences in paleodepth (association IIa in the shallow shelf setting of the Gulf Coastal Plain, e.g., Kellough, 1965), or sea floor sediments (association V in the hemipelagic Egyptian settings, e.g., Ernst et al., 2006).

4.4 Trophic and redox conditions

Biofacies 1, corresponding to coarse-grained sediment, contains the highest abundances of epibenthic morphogroups (Figs. 10 and 11), indicating well-oxygenated bottom waters, possibly close to the storm wave base. Oligotrophic to somewhat mesotrophic oxic environments occurred during the latest Paleocene in the deeper parts of the basin (Bass River) as indicated by the common presence of *G. beccariiiformis*, a bathyal species capable of invading oligotrophic shelf margins (Widmark and Speijer, 1997). At the more inland Wilson Lake, foraminiferal assemblages were less diverse and dominated by *B. virginiana*, indicative of a slightly more eutrophic, yet oxic environments.

The transitional biofacies with increasing abundance of association IIa taxa (*A. acutus* and *P. prima*) indicates more stressful environmental conditions, probably due to a change to moderately dysoxic bottom waters, but oxygenation levels were sufficient to sustain moderately diverse benthic assemblages. The unusually high proportion of stress-tolerant taxa of association IIa in biofacies 2 suggests that bottom water conditions were either persistently or intermittently stressful for the benthic biota. This foraminiferal species association has been linked to high surface productivity and/or lowered bottom water ventilation (e.g., Olsson and Wise, 1987; Gibson et al., 1993; Gibson and Bybell, 1994). The lower scores on DCA axis 2 point to the strongest oxygen depletion (extreme dysoxia) of all studied biofacies, probably extending from the sediment into the lowermost parts of the water column, as indicated by the near absence of large epibenthic morphogroups. High foraminiferal densities indicate that anoxia were not persistent.

Biofacies 3 is more diverse, characterized by stable abundance of association IIb species, indicating improvement of environmental conditions as more species were able to obtain a niche. Dysoxia no longer extended into the water column or were less continuous throughout the year, as indicated by the reappearance of epibenthic morphogroups (e.g., *C. succedens*) at Bass River (moderate to severe dysoxia), and to a lesser extent at Wilson Lake (extreme to severe dysoxia). The large proportion of endobenthic morphogroups and stress-tolerant taxa (association IIa) indicate persistent mesotrophic bottom water conditions. Biogenic magnetic nanoparticles are common in biofacies 2 and 3 (Kopp et al., 2007, 2009; Stassen et al., 2012b). Magnetite-precipitating bacteria thrive in suboxic pore water conditions at high iron bioavailability, but in anoxic conditions magnetite dissolves. The occurrence of the magnetic particles thus supports the reconstruction of dysoxic, but not anoxic conditions within the sediment as deduced from the benthic assemblages.

Biofacies 4 contains the most diverse PETM assemblage, indicating further improvement of bottom water oxygenation to somewhat less dysoxic (severe-moderate dysoxia) conditions, and the magnetic particles decline. The disappearance of biogenic magnetic nanoparticles and sudden dominance of *B. callahani* indicates a major environmental change within biofacies 5. At Dababiya (Egypt), a similar and coeval peak abundance of *B. callahani* (Stassen et al., 2012d) is linked to the occurrence of a high organic flux in a re-oxygenated basin (Ernst et al., 2006). Biofacies 5 thus probably reflects eutrophic oxic bottom waters, sustaining large populations of buliminids.

High foraminiferal diversity within biofacies 6 indicates a stable, not perturbed environment. More coarse-grained sediments suggest stronger turbulence and more oxygenated conditions, yet the abundance of endobenthic morphotypes and the consistent occurrence of *A. acutus* and *P. prima* indicate moderate dysoxic bottom water conditions and a high organic flux to the sea floor. Similar environmental conditions occurred during the deposition of biofacies 8. Biofacies 7 is enriched in lobate glauconite grains and contains a low-diversity foraminiferal assemblage, dominated by *B. virginiana*, indicative of higher food availability and severely dysoxic bottom water conditions.

4.5 Taphonomy

Although the foraminifera are generally well-preserved, specimens from the sandy facies are less translucent ('frosty') than those within the PETM clays, with a selective alteration of large epibenthic forms, indicating differential taphonomic effects in different lithologies. Upper Paleocene sediments in the NJCP accumulated relatively slowly (<1 cm/kyr), and sediment accumulation rates increased strongly during the PETM (Sluijs et al., 2007b; John et al., 2008; Stassen et al., 2012b). The very low numbers in the upper Paleocene most likely indicate taphonomic loss in these sandy strata and the higher foraminiferal numbers within the PETM clays are probably also indicative of increased test production. Condensation results in exceptionally high foraminiferal numbers without significant %P changes, as observed at the base of biofacies 2 at Bass River. The elevated foraminiferal numbers at the base of biofacies 7 correspond to very low %P, suggesting taphonomic processes in addition to condensation.

These sediment recovered by drilling has not been subject to secondary leaching in outcrop, thus dissolution may have occurred only syn- or early post-depositional, e.g. due to oxidation of organic material (e.g., Murray and Alve, 1999). Dissolution generally results in increased relative abundances of large, robust taxa (Nguyen et al., 2009), yet small fragile species are common throughout the studied intervals (e.g., *B. virginiana*), suggesting limited alteration by dissolution. Only thin intervals devoid of nannofossils in the uppermost Paleocene correspond to carbonate-poor, foraminiferal barren zones (Figs. 3 and 4; Gibbs et al., 2006a). *Tappanina selmensis* and planktic foraminifera are more common in the PETM clays, also indicating a lack of carbonate dissolution as both are more prone to dissolution (e.g., Nguyen et al., 2009). The low %P, very low foraminiferal numbers and a prominent drop in the carbonate content in biofacies 5 indicate partial dissolution (Fig. 4). This taphonomic change did not affect the paleoecologic signal much, because the moderately dissolution-resistant *B. callahani* (Nguyen et al., 2009) remains abundant.

Taphonomic modification also includes physical abrasion of foraminiferal tests in slowly accumulating sediments, subjected to constant sediment mixing through intense bioturbation, and re-suspension by strong tidal or wind-induced currents. Abrasion results in the selective loss of planktic and fragile benthic foraminiferal specimens at the sediment surface, and a residue of polished and/or broken large tests (Brunner and Biscaye, 2003; Murray, 2006). Foraminiferal tests of biofacies 1 remained long time near the sediment surface (low accumulation rates), consequently undergoing intense abrasion, leading to the observed impoverished assemblage, with damaged, large 'frosty' epibenthic morphotypes. Only small endobenthic morphotypes are better preserved, somewhat protected by their infaunal habitat, as the taphonomically active zone moved up slowly with sedimentation (Loubere et al., 1993).

Depth estimates of the Vincentown Fm. based on %P may thus be severe underestimated due to selective loss of planktic specimens. These periods of post-mortem abrasion and

dissolution within the taphonomically active zone were more intense in the shallower and sandier Wilson Lake than in the siltier Bass River setting. Mechanical test damage and dissolution are thus generally absent in the silty clays of the Marlboro Clay, in exception of biofacies 5. Glauconitic grains in the sandy to silty clays of the lower Eocene Manasquan Fm. are significantly larger and more lobular in shape than the surrounding quartz grains, indicating an authigenic origin in a lower-energy environment. Foraminiferal test damage is also less severe in the silty clays of the Manasquan Fm. than in the upper Paleocene Vincentown Fm.

5 DISCUSSION

5.1 Late Paleocene-early Eocene water depths and sedimentary regimes

Wilson Lake is positioned more proximal to the coast than Bass River (Fig. 1) and respectively inner to middle (WL: 30-70 m), and deep middle to outer neritic settings (BR: 80-150 m) are inferred (e.g., Zachos et al., 2006; John et al., 2008; Harris et al., 2010; Wright and Schaller, 2013). These estimates are mainly based on foraminiferal faunas and basin gradient modeling (e.g., Olsson and Wise, 1987; Browning et al., 1997a). This modeling technique integrates foraminiferal abundance data with the paleoslope gradient, but the paleodepth calibration is hampered by lack of accurate paleo-coastline positioning due to erosion of the nearshore facies. Backstripping analysis allows an assessment of the regional New Jersey sea level curve, indicating that minor fluctuations in sea level (falls ~10-20 m; rises ~10-40 m) occurred during the early Paleogene, with highest sea level reached during the early Eocene (Van Sickle et al., 2004; Kominz et al., 2008).

Various paleobathymetric approaches (based on lithology and foraminiferal assemblages) point to a significant sea-level change across the P-E boundary (Figs. 10 and 11), as has been long recognized (e.g., Olsson and Wise, 1987; Gibson et al., 1993). Olsson and Wise (1987) assumed an unconformity at the base of the Marlboro Clay (their 'unnamed unit') with an unknown rate of sea-level change across this hiatus. Recognition of the CIE led to the realization that this apparent New Jersey sea-level rise (60-70 m; Harris et al., 2010) must have occurred over less than about 10 kyr, which seems highly improbable or even impossible in a largely ice-free greenhouse world (DeConto and Pollard, 2003). Harris et al. (2010) thus argued that the paleodepth estimates for the Marlboro clay were overestimates due to non-specified severe environmental changes during the PETM, and that the paleodepth estimates for the Vincentown Fm. were correct. The paleodepth estimate of ~70-80 m for the Marlboro Clay at Bass River was accepted by Wright and Schaller (2013). In contrast, Stassen et al (2014) argued that the paleodepth estimates for the well preserved assemblages of the Marlboro Clay are correct (i.e. ~130 m for Bass River), and those for the Vincentown Fm. incorrect due to taphonomic changes. Nevertheless, a rapid eustatic sea-level rise has been reconstructed at about the PETM-onset worldwide, possibly reflecting the melting of small Antarctic ice sheets combined with steric sea-level rise (Speijer and Wagner, 2002; Sluijs et al., 2008), with estimates of PETM-related eustatic sea-level rise of ~20-40 m in the southern Tethys (Speijer and Morsi, 2002; Stassen et al., 2012a).

Therefore, a careful assessment of environmental and taphonomic changes is needed to evaluate the paleobathymetric development of the NJCP across the base of the CIE. We do not directly rely on the relationship between %P and water depth as this can be strongly distorted by taphonomy and anoxia (Van der Zwaan et al. 1990). We compare paleodepth estimates based on lithology, planktic foraminiferal abundance and benthic foraminiferal associations (biofacies

model). The different methods (Fig. 9) result in similar trends in sea-level change, but with different magnitudes (Figs. 10 and 11).

5.1.1. Late Paleocene (Biofacies 1)

The lithofacies in the NJCP have been interpreted in terms of paleobathymetry (Olsson and Wise, 1987). Their simple lithofacies model suggests deposition of uppermost Paleocene glauconitic sands and silts in middle neritic settings, in agreement with low %P. However, characteristic nearshore species recognized in other regions (*Anomalinoides umboniferus*, *Globulina gibba* and *Pararotalia perclara*; Olsson and Wise, 1987) are absent, as are bivalves and other invertebrates, indicating that water depths were never shallower than ~50 m over the studied interval. The benthic foraminiferal fauna indicates shallow outer neritic (WL: 100-110 m) to deeper outer neritic settings (BR: 140-150 m) during the latest Paleocene, with an inter-site depth difference in agreement with the paleoslope gradient, and estimates not influenced by exclusion of association Ila species. Such a deep shelf setting is supported by the common presence of *G. beccariiiformis*, diverse nannoplankton associations (Gibbs et al., 2006a), and the presence of a (at least seasonally) well-developed water column temperature and carbon isotope gradient (Zachos et al., 2006, 2007; John et al., 2008).

Our biofacies estimates indicate significantly greater depths than inferred from the accumulation of quartz-rich sands with low %P. We argue that the uppermost Paleocene sediments probably were subject to extensive winnowing leading to lag deposits of relatively large quartz grains, with significant taphonomic loss of planktic and epibenthic foraminifera, especially at the shallower Wilson Lake. Fair-weather and storm wave base, important levels in sediment dynamics, reach depths between 30 to 50 m in modern open shelf regions (Immenhauser, 2009), but sediments in deeper parts of the shelf may be subject to intense, episodic wave agitation or tidally-driven currents (e.g., Scott et al., 2003). In addition, bottom currents triggered by extreme storms or hurricanes can re-suspend sediments and scour the sea floor up to depths of 50 to 90 m (Teague et al., 2007). Offshore currents parallel to the coastline may also have been active (e.g., Huber et al., 2003). The sediment-starved New Jersey shelf (Browning et al., 2008) was gradually shallowing in the late Paleocene (Gibson and Bybell, 1994; Harris et al., 2010) and the slow accumulation of coarse grained sediments in deep-shelf settings may have been close to equilibrium, with re-suspension through vigorous bottom water currents.

5.1.2. PETM (transitional biofacies, biofacies 2-5)

The shift to more clayey sediments (Marlboro Clay, the onset of the PETM) suggests a significant sea-level rise, and the establishment of deep outer neritic settings (Olsson and Wise, 1987; Gibson et al., 1993). At both sites, a rapid increase of planktic foraminifera at the base of the CIE also suggests a significant shift to deeper waters, with water depth estimates during the PETM exceeding 150 m. A pronounced increase in water depth is also indicated by the onset of the benthic foraminiferal transitional biofacies and biofacies 2, resulting in water depth estimates of 130-145 m (120-130* m) at Wilson Lake, and approximately 140/135* m at Bass River. Note that we evaluate the effect of dysoxic bottom water conditions during the PETM by excluding the more opportunistic association Ila taxa from the biofacies paleodepth calculations (* indicates exclusion), as peak abundances of these species are questionable paleodepth indicators in poorly diverse assemblages. Nonetheless, paleodepth remained quite deep for the overlying more diverse

overlying PETM biofacies (WL 130-140 m/120-130* m; BR 135-140/125-135* m). Biofacies 5 is dominated by *B. callahani*, representing considerable environmental stress and therefore generating unreliable depths as such opportunistic species probably have wide ecologic niches without bathymetric preference.

PETM sediments are thus characterized by high abundances of planktic foraminifera, diverse nannoplankton assemblages, changes in the benthic foraminiferal assemblage, a large increase in the amount of clay, and virtual absence of sand-sized particles, all indicating an increase in water depth, a larger distance to the coast, and considerably less vigorous bottom currents. According to the Wilson Lake biofacies model, water depth increased by approximately 20-30 m at the CIE-onset, and remained high in the succeeding PETM biofacies. Such a rise in sea level cannot be discerned at Bass River due to the deeper initial setting.

The rising sea level created additional accommodation space and deepened the New Jersey shelf at least in part below the storm wave base, resulting in silty clay deposition. An indirect effect of sea-level rise may have been a change in geomorphology, influencing the strength of tidal currents. Yet, the shift to more clayey strata cannot have been caused by sea-level rise alone, because this alone would cause a simple coastward shift of depositional settings (e.g., PETM assemblages and lithology at Wilson Lake resembling pre-PETM settings at Bass River). This is not observed, as depositional settings changed significantly and in the same way along the NJCP (Stassen et al., 2012b), and probably most of the Salisbury embayment (Gibson and Bybell, 1994). These changes in depositional setting were related to global warming during the PETM, and include an intensified hydrologic cycle with variable seasonal precipitation patterns (intense wet season and prolonged dry season), and accelerated hinterland erosion of exposed kaolinite-rich Cretaceous deposits (Kopp et al., 2009; John et al., 2012). Intensified erosion resulted in increasing sediment loads in the rivers, supplying large amounts of suspended clay (Gibson et al., 1993; Zachos et al., 2006; Kopp et al., 2009), and leading to enhanced sediment accumulation rates at all sites. A major additional increase in accumulation rates occurred from the base of biofacies 3, although inter-site differences exist (Stassen et al., 2012b).

The elevated sediment supply, pulses of dinocysts with a low-salinity affinity (Sluijs and Brinkhuis, 2009), influx of kaolinite (Cramer et al., 1999; Gibson et al., 2000), and magnetofossil evidence all support establishment of a tropical river-dominated shelf (Kopp et al., 2009). Yet the high %P and stable isotope gradients between planktic genera (symbiont-bearing taxa calcifying in the mixed layer, non-symbiont bearing species in the thermocline, Zachos et al., 2006; John et al., 2008) indicate periods of non-turbulent surface water. The foraminiferal assemblages thus point to at least a seasonally clear photic zone, reduced vertical mixing (absence of bottom currents) and mud belt deposition in a deep shelf setting during the PETM, contrasting with the Paleocene sedimentary regime. Episodically occurring flood events would supply the large sediment flux (Kopp et al., 2009).

5.1.3. Early Eocene (post-PETM, biofacies 6-8)

The PETM clays are truncated by a regional sequence boundary (Stassen et al., 2012b), yet the exact magnitude of the associated sea-level fall cannot be deduced. The lobate and variable sized glauconite grains from the Manasquan Fm. indicate deposition below the storm wave base in a low-energetic, sediment-starved deep shelf environment (in analogy with modern >125 m settings, Porrenga, 1967; Immenhauser, 2009). The lower %P and coarser-grained lithology of the lower Eocene biofacies 6-8 at Wilson Lake indicate a return of shallower settings. Foraminiferal depth estimates for biofacies 6 are roughly 135/130* m, for biofacies 7:

100-120/100-115* m, and for biofacies 8: 115-130/100-130* m. The coarse fraction of biofacies 7 consists of almost pure glauconite, indicating strong winnowing or intensification of low-energy highly productive environments (dominance by *B. virginiana*), which may reflect regional upwelling as suggested by climate models (Huber et al., 2003).

5.2 Regional sequence stratigraphy

The NJCP is a well-studied passive continental margin, where Cenozoic sea-level changes have been extensively reconstructed because of an assumed simple subsidence history and good chronostratigraphic control (e.g., Harris et al., 2010), although this simplicity is questioned (e.g., Rowley et al., 2013). Important sequence boundary surfaces are recognized, yet attribution of the biofacies to specific systems tract is presently not possible due to the uncertain positioning of the maximum flooding surfaces, environmental disturbance during the PETM and multiple Eocene discontinuities with an erosive base.

Our studied intervals correspond to the Pa3a, Pa3b, E1 and E2 sequences (Browning et al., 1997b; Harris et al., 2010). Based on the %P (Harris et al., 2010) and the dinoflagellate *Spiniferites–Areoligera* ratio (Sluijs et al., 2008), a latest Paleocene transgression has been proposed, with a subtle sequence break at BR 359.05 m (Harris et al., 2010). Our observations indicate a %P increase below this level (Fig. 4), but no distinct pre-CIE benthic foraminiferal biofacies changes. The %P increase at Bass River most probably is a taphonomic signal (slightly better preservation of the planktic foraminifera), and no equivalent signal is present at Wilson Lake. We thus argue that no significant sea-level change occurred prior to the PETM, and transgression started at the P-E boundary (Figs. 10 and 11). All uppermost Paleocene glauconitic sands and silts of the Vincentown Fm. are thus attributed to the Pa3a sequence (Fig. 12). Our paleodepth estimates support a sea-level rise on the order of 20-30 m, followed by high sea level during the PETM. At all sites, the Pa3b sequence is confined to the CIE interval, encompassing the entire Marlboro Clay interval. A regional unconformity marks the top of Pa3b, indicative of a significant post-PETM sea-level fall, and partial removal of PETM sediments, varying between the different sites (Stassen et al., 2012b).

Eocene sequences E1 and E2 in the NJCP correspond respectively to nannoplankton Zones NP10 and NP11 (Browning et al., 1997b). The placement of the E1 sequence above the WL 96.32 m unconformity and E2 sequence above the WL 94.79 m unconformity results in a stratigraphic overlap of E2 at Wilson Lake with E1 at Bass River (Miller et al., 1998). The recognition of a previously unreported discontinuity at WL 93.15 m, recognizable by a decline of *B. virginiana* and a decrease in glauconite content, supports a sequence boundary for E2 at WL 93.15 m, with the E1 sequence subdivided in E1a and E1b (Fig. 12). The two closely spaced sequence boundaries at Bass River (346.94 and 347.05 m) may reflect a very thin E1a sequence.

5.3 Paleoenvironmental evolution from late Paleocene into early Eocene

The P-E boundary sequence in the NJCP has been the subject of high-resolution studies, including dinocysts (Sluijs and Brinkhuis, 2009), calcareous nannoplankton (Gibbs et al., 2006b) and stable isotopes (Zachos et al., 2006; John et al., 2008). We integrate these data with our foraminiferal abundance patterns and biofacies distribution into a paleoenvironmental reconstruction of surface and bottom water conditions (Fig. 12) within a regional stratigraphic framework (Stassen et al., 2012b).

5.3.1 Pre-PETM paleoenvironments

Benthic foraminiferal assemblages (biofacies 1) indicate for the latest Paleocene moderately dysoxic to oxic, mesotrophic (Wilson Lake) and oxic oligotrophic (Bass River) outer shelf environments, under the influence of energetic, tidal or storm-induced currents. The occurrence of *G. beccariiiformis* indicates a shelf-ward expansion of oligotrophic conditions, thus frontal upwelling was probably absent. Biofacies 1 was deposited in a sediment-starved, current-dominated, moderately productive open marine environment with normal surface water salinity (Fig. 12). This is in agreement with the dinocyst record indicative for energetic surface water conditions (Sluijs and Brinkhuis, 2009), and a diverse nannoplankton assemblage adapted to oligotrophic warm-water conditions (Gibbs et al., 2006b).

Limited precursor events occurred prior to the PETM, such as the start of the *Apectodinium* bloom and a higher *Spiniferites-Areoligera* ratio (Sluijs and Brinkhuis, 2009), rising surface water temperatures (Sluijs et al., 2007b), increased accumulation rates and declining grain-size at Wilson Lake (Stassen et al., 2012c) and increased kaolinite input (John et al., 2012). These pre-PETM environmental changes are corroborated by the increasing %P and diversity from WL 110.47 m and BR 357.71 m onwards, starting 40 to 45 kyr prior to the main environmental changes (Fig. 12, Stassen et al., 2012c). This may indicate a transition in the climate system through reduced storm activity and perhaps intensification of near-shore riverine influence.

5.3.2 PETM environments

Paleo-rivers in the Salisbury Embayment were relatively quiescent during the early Paleogene with only nearshore influences, but probably strongly intensified during the PETM (Kopp et al., 2009). The present-day analog for the NJCP during the PETM may be a tropical river-dominated shelf fed by large-scale energetic river systems, combining high surface water productivity with low-organic carbon bearing sediments, and thick sedimentary suboxic zones (Schumann et al., 2008). Associated shelf density currents control the (re)distribution of suspended mud, which is kept in suspension by internal turbulence, regionally reaching the shelf break (Leeder, 1999). For instance, during periods of high river discharge, the Amazon plume reaches out to about 100-200 km from the shoreline, before being deflected by strong offshore currents. Similar dynamics may have developed in an Appalachian-fed deltaic system, with variable clay accumulation in a wide mud belt (Kopp et al., 2009; Stassen et al., 2012b).

The overall controlling parameter of benthic communities within this mud belt was probably the long-lasting oxygen deficiency and the increased organic fluxes to the sea floor. The succession of different biofacies indicates transitional changes in bottom water conditions (Fig. 12). Conditions that may have pushed bottom waters to hypoxia (oxygen deficiency) in the NJCP include increased primary production, thus higher oxygen consumption rates (Gibbs et al., 2006b), intensification of water column stratification triggered by fresh water discharge (Sluijs and Brinkhuis, 2009), and substantially higher PETM temperatures (Zachos et al., 2006; John et al., 2008). However, the consistent presence of benthic biota and magnetofossils exclude the occurrence of long-term anoxia.

Near-coastal settings on such river-dominated shelves are characterized by reduced phytoplankton productivity and rapid accumulation of allochthonous organic matter, whereas increased stratification regulates the water column ventilation in the more distal, and less turbid settings (e.g., Bianchi et al., 2010). High rates of mud accumulation in the NJCP and high

planktic foraminiferal abundances in combination with a vertical isotope gradient in different genera of planktic foraminifera (Zachos et al., 2006; John et al., 2008) indicate non-turbid open marine conditions during at least part of the year, in a distal, outer shelf setting. The lack of terrestrial palynomorphs in the NJCP (Zachos et al., 2006) could be due to scarce vegetation in the hinterland, but this is not supported by vegetation modeling (Herold et al., 2014), and is thus consistent with a setting remote from the river discharge area.

In modern mud belts close to a major river outflow, seasonally developing hypoxia are common (van der Zwaan and Jorissen, 1991). For example, in the Gulf of Mexico near the Mississippi River outflow, the development of hypoxia begins with spring runoff, reaching a maximum during the summer, then disappearing during autumn storm mixing (Osterman, 2003). Biofacies in mud belts surrounding large river mouths therefore commonly show a systematic seasonal increase of less diverse benthic fauna, which can be used as a proxy for shelf hypoxia (e.g., Culver and Buzas, 1983; van der Zwaan and Jorissen, 1991; Osterman, 2003; Gooday et al., 2009). Species from the association Ila are the most common taxa in PETM assemblages, with only rare occurrence in the uppermost Paleocene sediments. We consider that they represent such a river-influenced foraminiferal community. Association Ila probably reflects a seasonal signal of stress-tolerant taxa (ecologic generalists), taking advantage of the high food availability and low competition during hypoxic conditions, whereas the total dead assemblage contains a mixture of assemblages reflecting the different seasonal conditions (remaining benthic foraminiferal fauna).

The foraminiferal data indicate a sea-level rise at the PETM onset (transitional fauna), followed by the establishment of poorly diverse foraminiferal assemblages. The dominance of taxa of association Ila (*T. selmensis*, *A. acutus*, and *P. prima*) in the lower part of biofacies 2 is possibly indicative of year-round strong hypoxic (extreme dysoxia) conditions at high organic flux during the PETM peak warming (≤ 40 kyr after onset, Fig. 12). Climate during PETM peak warming was probably warm and humid (Bowen et al., 2004), consistent with increased mean precipitation rates in the northern mid latitudes (Winguth et al., 2010). We thus reconstruct a regional prodeltaic environment in a warm humid climate, with a buoyant hyperpycnal plume and mud flow related to regular periods of increased river discharge (biofacies 2). Stratification could have been thermal and/or salinity driven, in the absence of vigorous bottom currents. Runoff periods (increased riverine nutrient supply) provoked continuous eutrophication of the outer shelf and establishment of long-lasting river-influenced foraminiferal communities. Surface salinity did not fall severely in view of the highly diverse planktic biota, and the lack of persistently abundant low-salinity tolerant dinocysts in the early stages of the PETM, although the genus *Apectodinium* was likely euryhaline (Sluijs and Brinkhuis, 2009). Increasing abundances of foraminiferal association Iib taxa and increasing diversity towards the top of biofacies 2 indicate a weakening of constant dysoxia at the sea floor and probably record the gradual evolution of a warm humid climate to a climate system with seasonally variable precipitation patterns (Fig. 12).

Accumulation rates increased significantly 40 kyr after the onset of the PETM (Stassen et al., 2012b), probably indicating the establishment of extreme, monsoon-like seasonal precipitation patterns during brief wet seasons and prolonged dry seasons (Zachos et al., 2006). The combination of diverse planktic biota and highest abundances of low-salinity tolerant dinocysts also points to episodic, probably seasonal, salinity changes, or longer duration of the oxygenated season. Increased diversity and more stable foraminiferal abundances in biofacies 3 and 4 suggest a general amelioration of environmental bottom-water conditions. These biofacies are therefore interpreted as the result of weakened persistent stratification and cyclic flood events, creating pulsed organic fluxes and periodic dysoxia. Association Ila species still flourished under seasonal perturbations, and under more stable conditions relatively diverse and more even

foraminiferal faunas occurred (associations IIb and IV), although the water column was not fully oxygenated during any part of the year.

Biofacies 5 corresponds to the final CIE recovery, starting 95 kyr after the PETM onset (Stassen et al., 2012b). The strong dominance of *B. callahani* coincides with blooms of dinocysts indicative of eutrophic conditions. Reduced foraminiferal abundance is probably caused by dissolution, reflecting increased vertical mixing due to pycnocline weakening and/or increasing tidal current or storm activity (coeval siltier strata at Ancora, Stassen et al., 2012b), and resulting enhanced oxidation in the taphonomically active zone. The absence of the river-influenced foraminiferal associations suggests that river influence on the outer shelf setting was declining, although river-induced eutrophication of the shelf continued (Fig. 12).

5.3.3 Post-PETM paleoenvironments

Post-PETM biofacies lack evidence of dysoxia and stratification, suggesting a more ventilated basin with eutrophic, slightly dysoxic bottom-water conditions, in part under the influence of frontal upwelling. The recurrence of river-influenced assemblages (association IIa) at the top of studied interval coincided with new pulses of low saline tolerant dinocysts (Fig. 12), marking the return of episodic river discharges towards the outer shelf. This riverine influence was too weak to disturb the benthic communities.

5.4 Shallow water biotic turnover during the PETM

At the onset of the PETM, deep-sea benthic foraminifera suffered severe extinction (Tjalsma and Lohmann, 1983; Thomas, 1989, 2007). Extinction was considerably less severe on the southern Tethyan shelves, as most shelfal taxa reappeared in the aftermath of the PETM (Speijer et al., 1995, 1996; Stassen et al., 2012a), with limited net ecosystem changes (Stassen et al., 2012d). Most taxa which became extinct have a deep-water affinity, including *G. beccariiformis* and *Angulogavelinella avnimelechi* (Speijer et al., 1996; Speijer and Schmitz, 1998; Ernst et al., 2006). Although there were major environmental changes at the onset of the PETM in the NJCP, with a large biotic response, only *G. beccariiformis* became extinct, and *Bulimina cacumenata* and *B. callahani* first appeared during the PETM. The appearance of these buliminids is migratory, because they were extant in the Paleocene (*B. cacumenata*: Gulf Coastal Plain; e.g., Cushman, 1951 and *B. callahani*: Egypt; e.g., Ernst et al., 2006).

Most disappearances at the P-E boundary in the NJCP were temporary, as species reappeared in the upper part of the Marlboro Clay or the Manasquan Fm., resulting in a minor taxonomic turnover compared to the extinction in the deep-sea. In addition, the presence of a transitional biofacies at the PETM onset indicates a gradual biotic response to the massive release of greenhouse gasses. We speculate that the extinction rate in the NJCP was very low because most species could survive in refugia which remained oxygenated, either in time (seasonally?) or in space (adjacent embayments?). Cosmopolitan *G. beccariiformis* was not capable of retaining a suitable niche, because this species was adapted to oligotrophic deep shelf and bathyal settings. The Paleocene New Jersey shelf occurrence reflects the upper limits of its distribution, and the combination of shelf eutrophy and perturbation of the deep-sea habitat (Thomas, 1998; Winguth et al., 2012) pushed this species to extinction.

6 CONCLUSIONS

Foraminiferal analysis allowed the recognition of a stratigraphic succession of eight biofacies at Wilson Lake and Bass River, reflecting changes in oxygenation, organic fluxes and paleodepth across the PETM in the New Jersey Coastal Plain. The biotic impact of the PETM was significant and oxygen deficiency was probably the major controlling parameter, but net extinction of benthic species was limited.

- The uppermost Paleocene sandy Vincentown Formation was deposited in an outer neritic setting with mesotrophic to oligotrophic, oxic to moderately dysoxic bottom conditions. Its paleodepth previously inferred as inner neritic was underestimated due to taphonomic effects reducing the number of planktic foraminifera. No significant foraminiferal events preceded the onset of the PETM, although a gradual transition into the PETM climate system may have occurred, starting 40 kyr prior to the CIE onset.
- The onset of the PETM marks the diminution of Paleocene benthic communities, but the overall taxonomic turnover is insignificant compared to the deep-sea extinction event, with only one species becoming extinct in this shelf region (*Gavelinella beccariiiformis*).
- Benthic communities were severely disrupted during the early stages of the PETM peak warming (< 40 kyr) with the establishment of an outer shelf river-influenced assemblage, in response to persistent stratification, oxygen depletion and eutrophication. Sediments accumulated in a continuously dysoxic mud belt system during the PETM. The later stages of the PETM (40-70 kyr) and initial recovery (70-95 kyr) were characterized by seasonal variations in dysoxia, possibly related to pulses of riverine outflow due to extreme seasonal precipitation patterns.
- The final recovery at Bass River is associated with re-oxygenation of the sea floor, by increased vertical mixing at continued eutrophic conditions, starting ± 95 kyr after the onset of the PETM. No complete faunal recovery occurs below the Eocene unconformities.
- Post-PETM environments were meso- to eutrophic, yet sufficiently ventilated to avoid severe benthic stress.

7 ACKNOWLEDGEMENTS

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APPENDIX

Supplementary data associated with this article can be found in the online version. Appendix A: Census data of the benthic foraminifera in the larger than 63 μm fraction. Appendix B: Supplementary information on paleobathymetric preference of the New Jersey Coastal Plain benthic foraminifera. Appendix C: Taxonomic notes.

10 FIGURE CAPTIONS

Figure 1

A: Paleogeographic reconstruction of North America during the Paleocene (60 Ma, modified after Blakey's maps, <http://cpgeosystems.com>). B: Enlarged view of the New Jersey Coastal Plain with the position of the Wilson Lake and Bass River sites. Fall Line represents the boundary between undeformed Cretaceous-Cenozoic sediments and pre-Cretaceous basement rocks.

Figure 2

Detailed stratigraphy of the Wilson Lake and Bass River sites. Nannoplankton ranges after Aubry et al. (2000, medium gray), Gibbs et al. (2006a, black) and Laurel Bybell (pers. comm., light gray). Isotope records after Zachos et al. (2006; WL bulk carbonate), Sluijs et al. (2007b, WL and BR dinocyst organic material), John et al. (2008, BR bulk carbonate) and Stassen et al. (2012b, WL and BR foraminiferal isotope records).

Figure 3

Weight percentage of the fraction larger than 63 micrometer ($\text{wt}\% > 63 \mu\text{m}$), carbonate content (% carbonate, Zachos et al., 2006) and general foraminiferal parameters such as planktic-benthic ratio (%P), planktic and benthic foraminifera per gram sediment (respectively PF/gram and BF/gram) and benthic foraminiferal diversity indices, such as Shannon diversity number ($H(s)$) and Dominance (D).

Figure 4

Weight percentage of the fraction larger than 63 micrometer ($\text{wt}\% > 63 \mu\text{m}$), carbonate content (% carbonate, John et al., 2008) and general foraminiferal parameters such as planktic-benthic ratio (%P), planktic and benthic foraminifera per gram sediment (respectively PF/gram and BF/gram) and benthic foraminiferal diversity indices, such as Shannon diversity number ($H(s)$) and Dominance (D).

Figure 5

Benthic foraminiferal abundances of the most common taxa at Wilson Lake ($>2.5\%$ in at least one sample). The division into biofacies is based on the varying proportions of benthic foraminiferal species associations (Ia to V).

Figure 6

Benthic foraminiferal abundances of the most common taxa at Bass River ($>2.5\%$ in at least one sample). The division into biofacies is based on the varying proportions of benthic foraminiferal species associations (Ia to V).

Figure 7

Cluster analysis (Pearson correlation paired groups) indicates several benthic foraminiferal species associations (I to V); the most common taxa are underlined ($>5\%$ in at least one sample). Association I taxa have highest abundances within uppermost Paleocene and lower Eocene sediments. Species of associations IIa to IV have highest abundances within the PETM (CIE

‘core’). Association V contains taxa that are mainly dominant with the upper part of the PETM (CIE recovery) and lower Eocene (Manasquan Fm.).

Figure 8

A) Bivariate plots of sample scores on the first and second detrended correspondence analysis axes and paleoecologic interpretation (nomenclature of oxygen levels after Tyson and Pearson, 1991). This two-dimensional ordination of the samples supports the subdivision into separated biofacies. B) The ordinations of the most common taxa (>5% in at least one sample) are plotted along the axes. C) Summary of paleoecologic interpretation of the different species association.

Figure 9

New Jersey Coastal Plain paleodepth proxies, A: Paleocene and Eocene planktic-benthic ratios plotted versus their interpreted paleodepths (based on data of Youssefina, 1978; Olsson and Wise, 1987; Browning et al., 1997a). B: Lithofacies model expressing the relationship between water depth and dominant lithology (modified after Olsson and Wise, 1987). C: Summary of paleodepth preference of the 5 discussed foraminiferal species associations (see supplementary data for more information).

Figure 10

Paleodepth estimations are based on trends in lithology, planktic foraminiferal abundances and varying benthic species abundances (species associations). Interpretation of the high-food/low-oxygen indices (morphogroup proportions) indicates a close relationship with the distribution of the different foraminiferal associations, mimicking the axes of the detrended correspondence analysis (axis 1: bottom water oxygenation and axis 2: organic flux to the sea floor).

Figure 11

Paleodepth estimations are based on trends in lithology, planktic foraminiferal abundances and varying benthic species abundances (species associations). Interpretation of the high-food/low-oxygen indices (morphogroup proportions) indicates a close relationship with the distribution of the different foraminiferal associations, mimicking the axes of the detrended correspondence analysis (axis 1: bottom water oxygenation and axis 2: organic flux to the sea floor).

Figure 12

Summary of the biofacies, associated paleoenvironmental indicators and the interpreted paleoenvironmental reconstructions in this study (based upon Sluijs et al., 2007b; Sluijs and Brinkhuis, 2009; Stassen et al., 2012b; see text for discussion).

11 TABLE CAPTIONS

Table 1

Detailed positions of the biofacies intervals stratigraphic assignment as recognized at Wilson Lake and Bass River (nannoplankton: NP; carbon isotope excursion subdivision: CIE and sequence assignment: Seq.; stratigraphic subdivision after Stassen et al., 2012b).

Table 2

Averaged values of the foraminiferal parameters in the uppermost Paleocene to lowermost Eocene biofacies (planktic-benthic ratio: %P, planktic and benthic foraminifera per gram:

PF/gram and BF/gram, weight percentage >63 μm : wt%, total abundances of species associations, number of taxa: S, Fisher-alpha: $F(\alpha)$, Shannon-Weaver: $H(s)$ and dominance: D).

12 PLATE CAPTIONS

Plate 1

Foraminiferal species association Ia and Ib: Paleocene and continuous occurrences. Scale bar represents 100 μm .

- 1) *Pyramidulina* group (WL 110.37 m)
- 2) *Stilostomella* group, e.g., *Stilostomella plummerae* (Cushman) (WL 110.37 m)
- 3) *Bulimina midwayensis* (Cushman and Parker) (WL 110.37 m)
- 4) *Bulimina virginiana* (Cushman) (WL 95.43 m)
- 5) *Bulimina hornerstownensis* Olsson (WL 96.35 m)
- 6) *Tritaxia clavata* (Cushman) (BR 362.39 m)
- 7) a/b *Pullenia* species, e.g., *Pullenia quinqueloba* (Reuss) is most frequent (BR 352.36)
- 8) a/b/c *Paralabamina lunata* (Brotzen) (WL 100.31 m)
- 9) a/b/c *Anomalinoides compressus* (Olsson) (WL 110.06 m)
- 10) a/b/c *Anomalinoides affinis* (Hantken) (BR 357.33 m)
- 11) a/b/c *Anomalinoides affinis* (Hantken) (WL 95.43 m)
- 12) a/b/c *Osangularia plummerae* Brotzen (WL 95.43 m)
- 13) a/b/c *Cibicidoides alleni* (Plummer) (WL 110.37 m)
- 14) a/b/c *Cibicidoides howelli* (Toulmin) (BR 357.33 m)
- 15) a/b/c *Cibicidoides howelli* (Toulmin) (WL 110.37 m)
- 16) a/b/c *Gavelinella beccariiiformis* (White) (BR 357.33 m)
- 17) a/b/c *Gavelinella beccariiiformis* (White) (WL 110.37 m)

Plate 2

Foraminiferal species associations IIa, IIb, III and IV: mainly PETM occurrences. Scale bar represents 100 μm .

- 1) *Spiroplectinella laevis* (Roemer) (BR 349.32 m)
- 2) *Ammobaculites expansus* Plummer (WL 108.84 m)
- 3) *Bulimina ovata* d'Orbigny (WL 100.31 m)
- 4) *Fursenkoina wilcoxensis* (Cushman and Ponton) (WL 100.31 m)
- 5) *Fursenkoina aquiensis* Nogan (WL 100.31 m)
- 6) *Pseudouvigerina wilcoxensis* Cushman and Ponton (WL 100.31 m)
- 7) *Uvigerina elongata* Cole (WL 108.84 m)
- 8) *Stainforthia* sp.1 (BR 352.36 m)
- 9) *Eouvigerina whitei*? Brotzen (BR 106.41 m)
- 10) *Tappanina selmensis* (Cushman) (WL 106.41 m)
- 11) *Siphogenerinoides brevispinosa* Cushman (BR 350.87 m)
- 12) *Uvigerina rippensis* Cole (WL 108.84 m)
- 13) *Coryphostoma midwayensis* (Cushman) (WL 106.41 m)
- 14) *Globocassidulina subglobosa* (Brady, WL 95.43 m)
- 15) *Globocassidulina subglobosa* (Brady) (WL 100.31 m)
- 16) a/b/c *Gyroidinoides subangulatus* (Plummer) (BR 351.18 m)
- 17) a/b/c *Pulsiphonina prima* (Plummer) (WL 108.84 m)
- 18) a/b/c *Alabamina midwayensis* Brotzen (WL 108.84 m)

- 19) a/b/c *Anomalinoides acutus* (Plummer) (WL 108.84 m)
- 20) a/b/c *Valvalabamina depressa* (Alth) (WL 108.84 m)
- 21) a/b/c *Cibicidoides succedens* (Brotzen) (BR 349.32 m)
- 22) a/b/c *Cibicidoides succedens* (Brotzen) (WL 95.43 m)

Plate 3

Foraminiferal species association V: PETM recovery and early Eocene occurrences. Scale bar represents 100 μ m.

- 1) *Dentalina-Dentalinoides* group: *Dentalinoides* (cf.) *longiscata* (d'Orbigny) (WL 108.84 m)
- 2) *Gaudryina pyramidata* (Cushman) (WL 96.04 m)
- 3) *Gaudryina pyramidata* (Cushman) (BR 358.16 m)
- 4) *Pseudouvierina triangularis* Jennings (WL 95.43 m)
- 5) *Bulimina cacumenata* Cushman and Parker (WL 96.04 m)
- 6) *Bulimina callahani* Galloway and Morrey (WL 96.04 m)
- 7) *Turrilina brevispira* ten Dam (WL 95.43 m)
- 8) a/b/c *Alabamina wilcoxensis* Toulmin (WL 95.43 m)
- 9) a/b/c *Gyroidinoides aequilateralis* (Plummer) (WL 95.43 m)
- 10) a/b/c *Gyroidinoides aequilateralis* (Plummer) (BR 352.36 m)
- 11) a/b *Lenticulina* spp. (WL 106.41 m)
- 12) a/b/c *Anomalinoides zitteli* (Leroy) (WL 95.43 m)
- 13) a/b/c *Oridorsalis plummerae* (Cushman) (BR 357.33 m)
- 14) a/b/c *Neoeponides mexicanus* (Cushman) (WL 96.04 m)
- 15) a/b/c *Neoeponides lotus* (Schwager) (WL 100.31 m)

Stratigraphy				Wilson Lake				Bass River			
biofacies	NP zone	CIE	Seq.	base	top	lithology	associations Ia, Ib, IIa and V	base	top	lithology	associations
8	NP10b/d- NP11	post	E2	93.15	90.53	glauconitic clayey sand		345.83	/	very glauconitic clays	not studied
	unconformity					unconformity at 93.15 m				unconformity at 345.83 m	
7	NP10a-b/d	post	E1b	94.79	93.15	very glauc. clayey sand	Ia	346.94	345.83	very glauconitic clays	not studied
	unconformity					unconformity at 94.79 m				unconformity at 346.94 m	
6	NP10a	post	E1a	96.32	94.79	glauconitic clayey silt	Ia, IIa and V	347.05	346.94	very glauconitic clays	not studied
	unconformity					unconformity at 96.32 m				unconformity at 347.05 m	
5	NP10a	recovery	Pa3b	not present (eroded)				348.86	347.05	dark greenish gray clay	V
4	NP10a	recovery	Pa3b	not present (eroded)				352.82	348.86	dark greenish gray clay	Ib, IIa, IV and V
3	NP10a	peak	Pa3b	103.65	96.32	dark clay	IIa and IIb	356.3	352.82	dark greenish gray clay	Ib, IIa and IIb
	change in sedimentary regime					tipping point at 103.65 m				tipping point at 103.65 m	
2	NP9b-10a	peak	Pa3b	109.27	103.65	dark clay	IIa and IIb	357.18	356.3	dark greenish gray clay	IIa
transitional	?	onset	Pa3b	109.50	109.27	(glauconitic) clayey silt	Ia, IIa and V	357.29	357.18	dark greenish gray clay	IIa (mixture)
barren	?	onset	?	109.99	109.50	glauconitic (clayey) sand	barren	no dissolution			
1	NP9a	pre	Pa3a	110.47	109.99	glauconitic (clayey) sand	Ia and Ib	357.71	357.29	glauc. silty micaceous clay	Ib
	minor pre-PETM change					tipping point at 110.47 m				tipping point at 357.71 m	
1	NP9a	pre	Pa3a	111.74	110.47	glauconitic (clayey) sand	Ia and Ib	362.86	357.71	glauc. silty micaceous clay	Ib
barren	?	pre	Pa3a	112.78	111.74	glauconitic (clayey) sand	barren	365.94	362.86	glauc. silty micaceous clay	barren

Table
1

Wilson Lake		general parameters				Species association (% of total benthic)							diversity			
biofacies		P/B	PF/gram	BF/gram	wt%	Ia	Ib	IIa	IIb	III	IV	V	S	F(α)	H(s)	D
8		12	27	235	14	25	22	27	0	0	1	15	18	5.0	2.2	0.2
7		12	289	3296	69	58	12	6	1	0	3	17	20	4.8	1.8	0.3
6		26	441	1162	35	16	11	20	8	1	3	38	30	8.5	2.9	0.1
5		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
3		66	754	328	1	5	6	41	42	1	2	2	17	3.9	2.1	0.2
2		78	1006	241	1	5	3	73	16	0	1	1	15	3.3	1.8	0.2
transition		31	9	19	5	18	5	46	3	4	2	19	20	5.5	2.2	0.2
1		4	4	28	57	58	28	1	3	2	1	4	19	4.9	1.9	0.3

Bass River		general parameters				Species association (% of total benthic)							diversity			
biofacies		%P	PF/gram	BF/gram	wt%	Ia	Ib	IIa	IIb	III	IV	V	S	F(α)	H(s)	D
8		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
7		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
5		19	12	33	1	10	7	5	0	0	2	76	17	3.9	1.8	0.3
4		77	2518	729	1	8	15	32	7	0	19	16	31	8.6	2.6	0.1
3		78	3694	1121	1	0	24	34	23	1	9	8	25	6.5	2.4	0.1
2		83	17519	3290	4	1	12	65	14	1	3	5	17	4.1	1.9	0.2
transition		59	78	53	4	2	22	50	3	1	8	11	23	6.4	2.4	0.1
1		15	167	355	13	9	71	3	3	0	3	6	22	5.9	2.2	0.2

Table 2

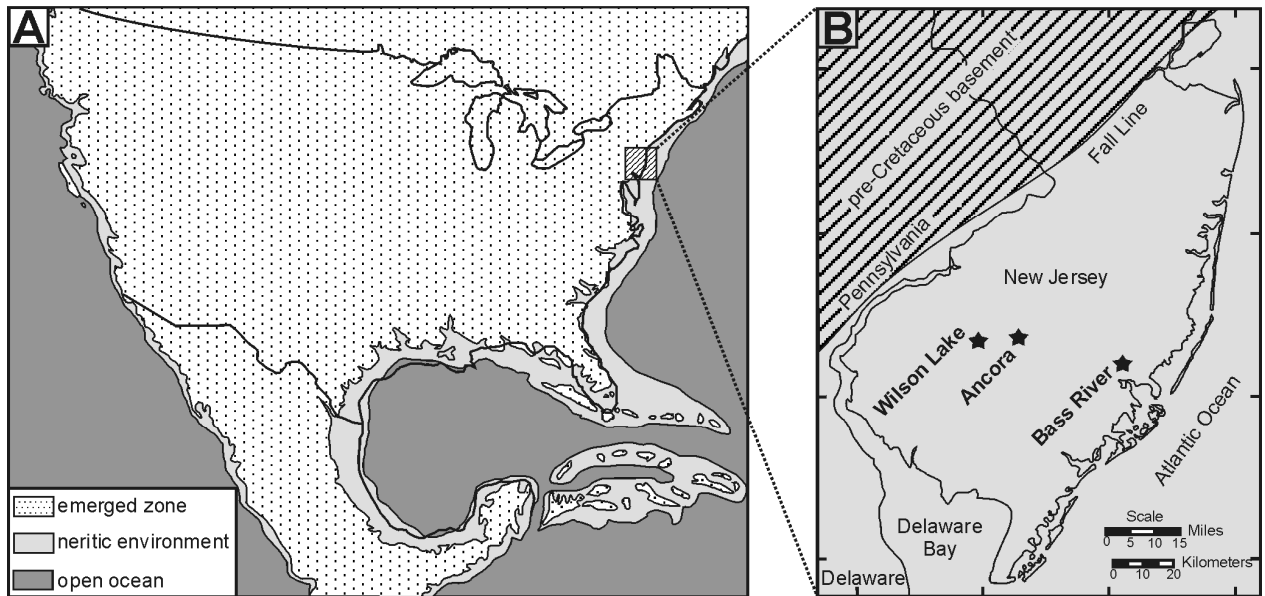
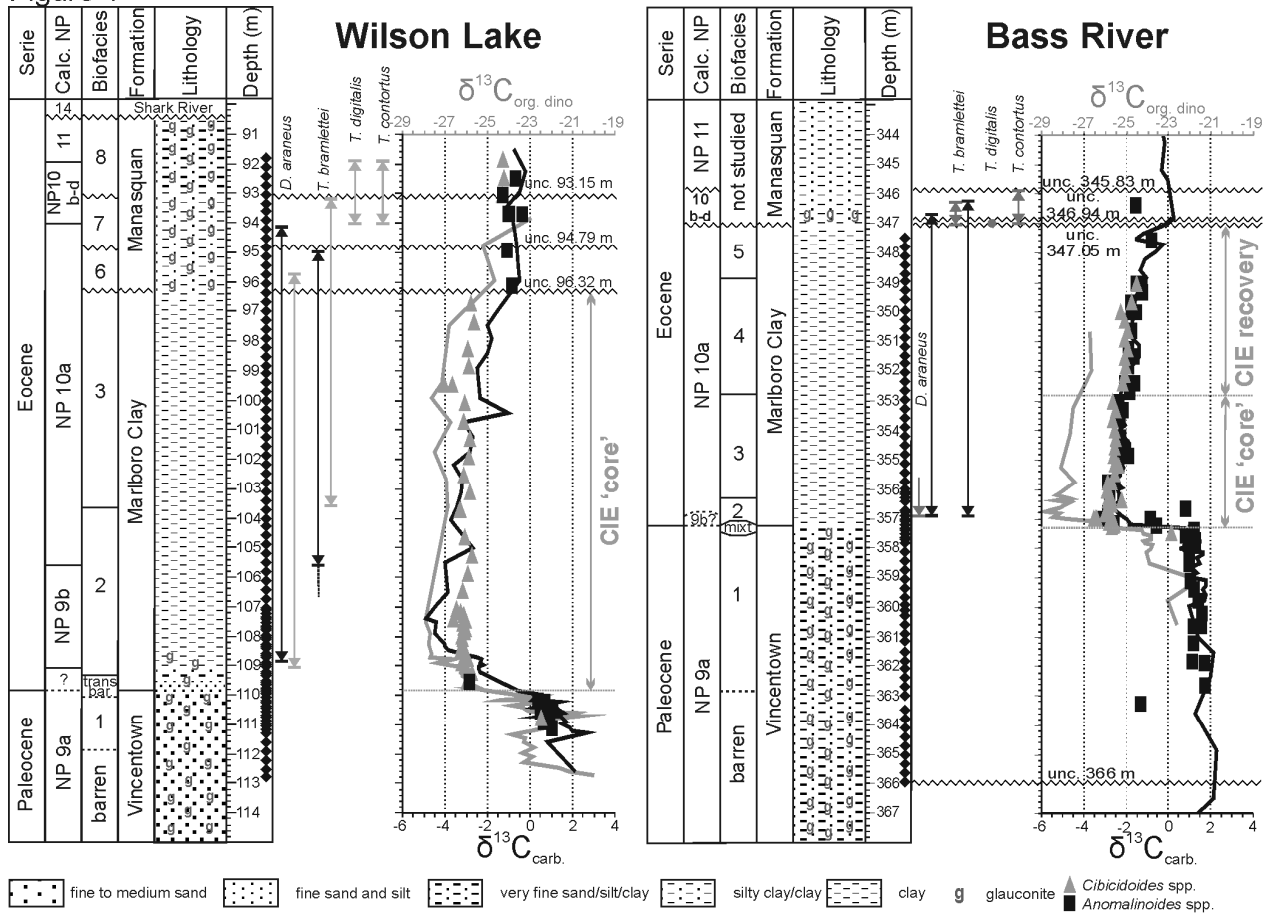


Figure 1



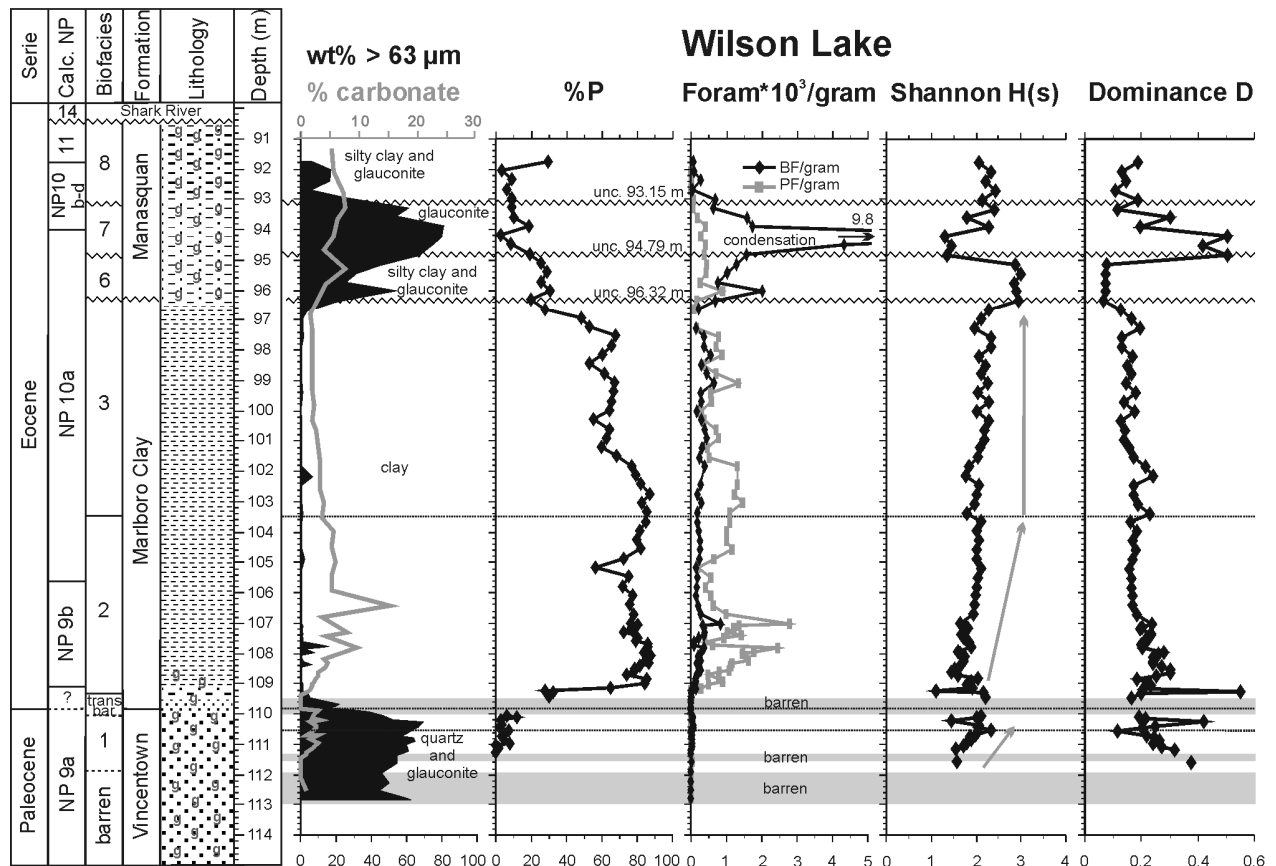


Figure 3

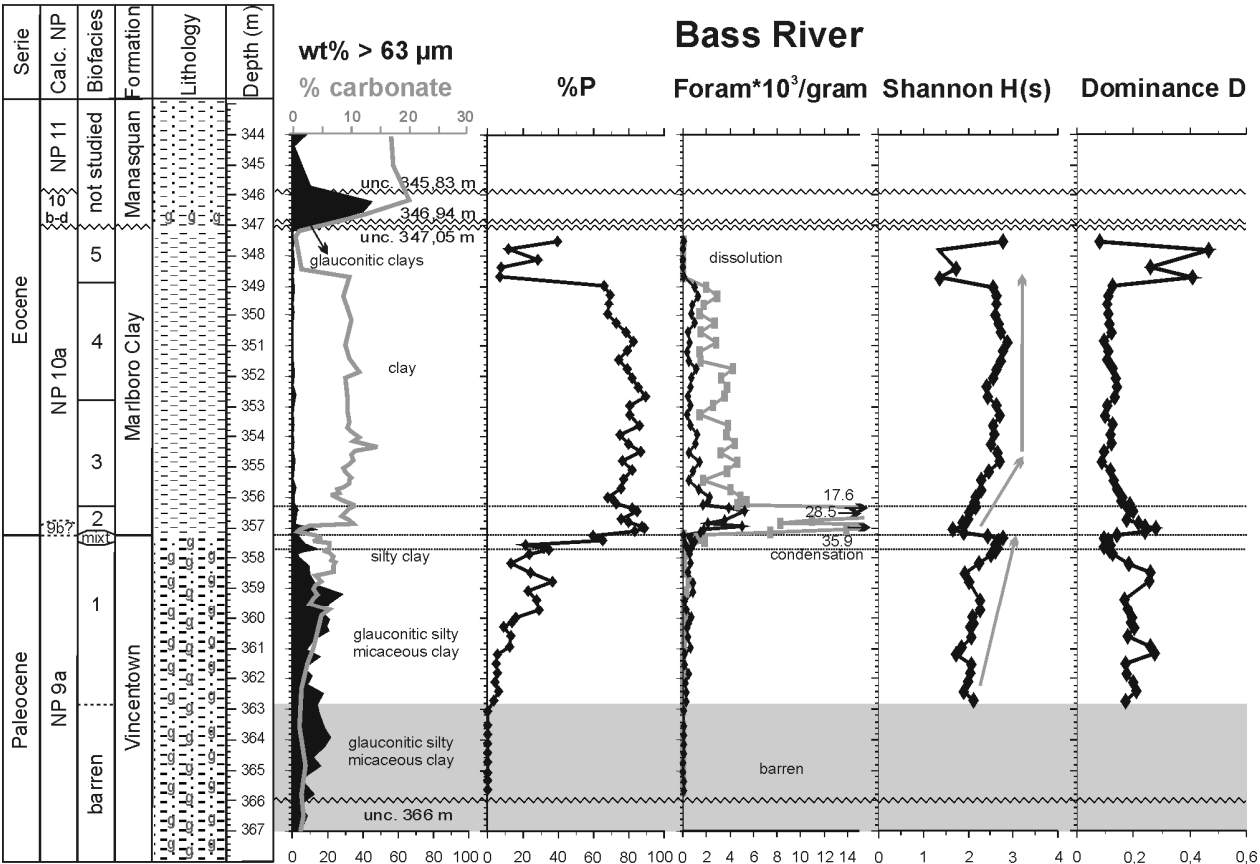


Figure 4

Wilson Lake

Serie	Calc. NP	Biota	Formation	Lithology	Depth (m)
Eocene	NP 10a	3	Manasquan	Shark River	91
					92
					93
					94
					95
					96
					97
					98
					99
					100
Paleocene	NP 9b	2	Marlboro Clay	Shark River	101
					102
					103
					104
					105
					106
					107
					108
					109
					110
Paleocene	NP 9a	1	Vincentown	Shark River	111
					112
					113
					114
					115

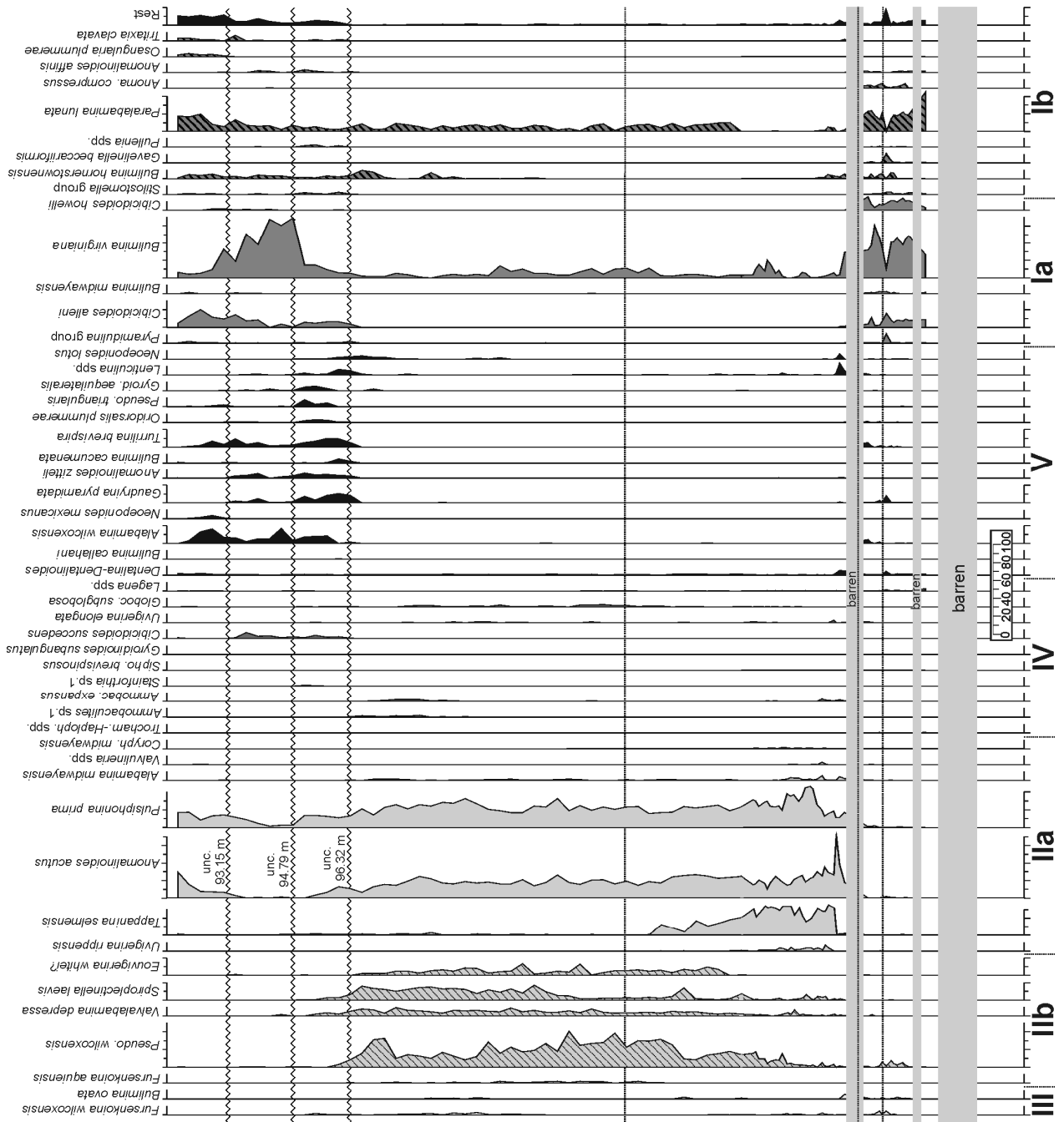


Figure 5

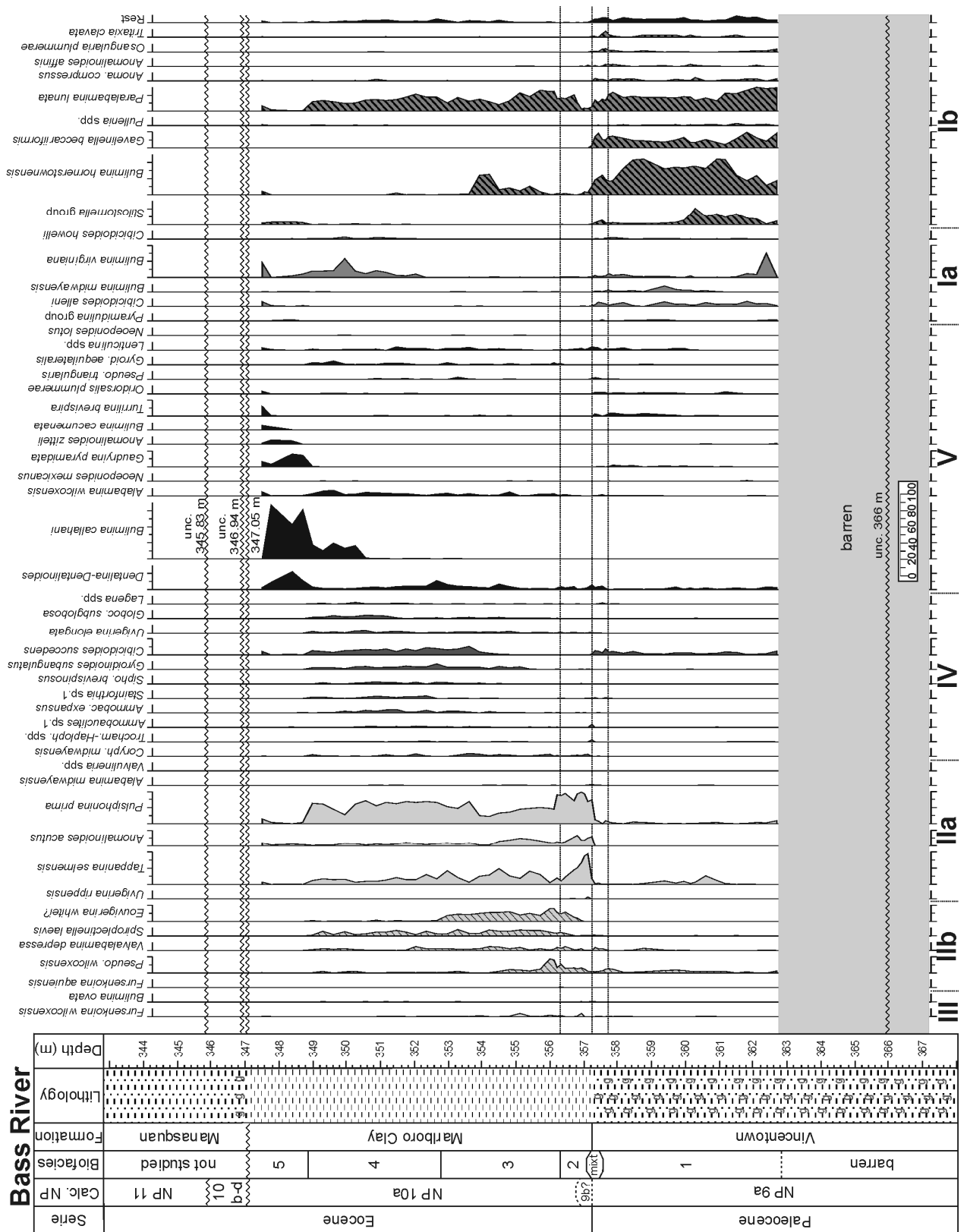


Figure 9

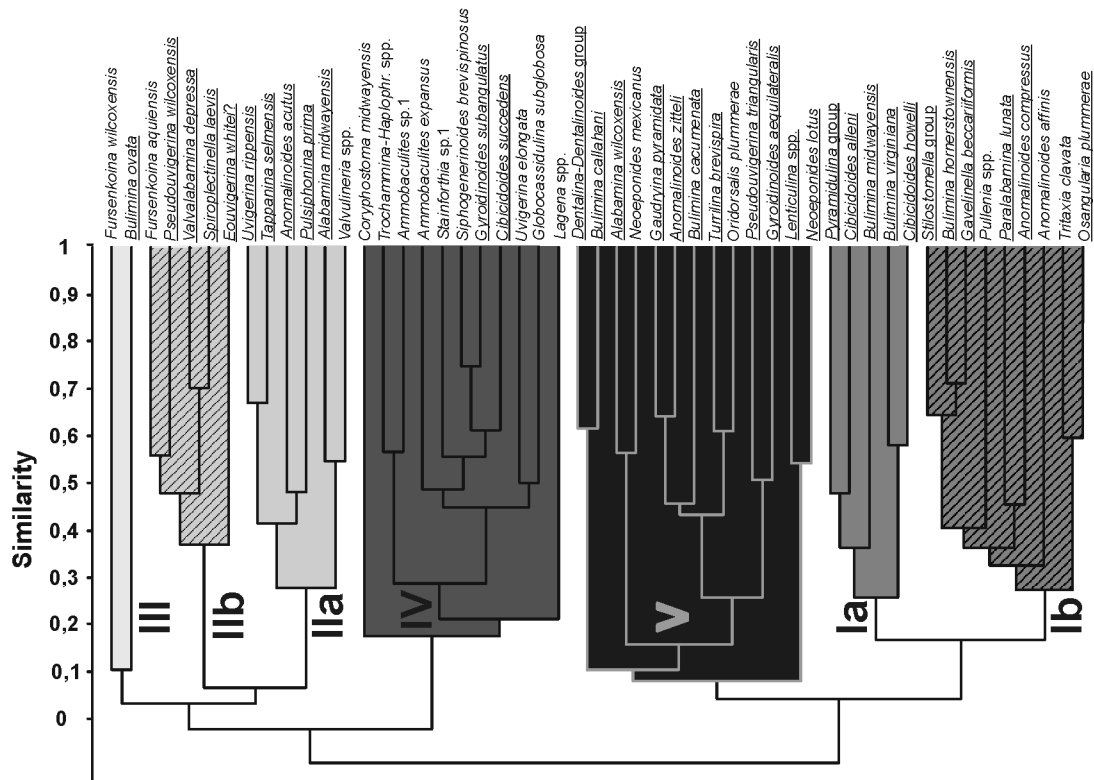


Figure 7

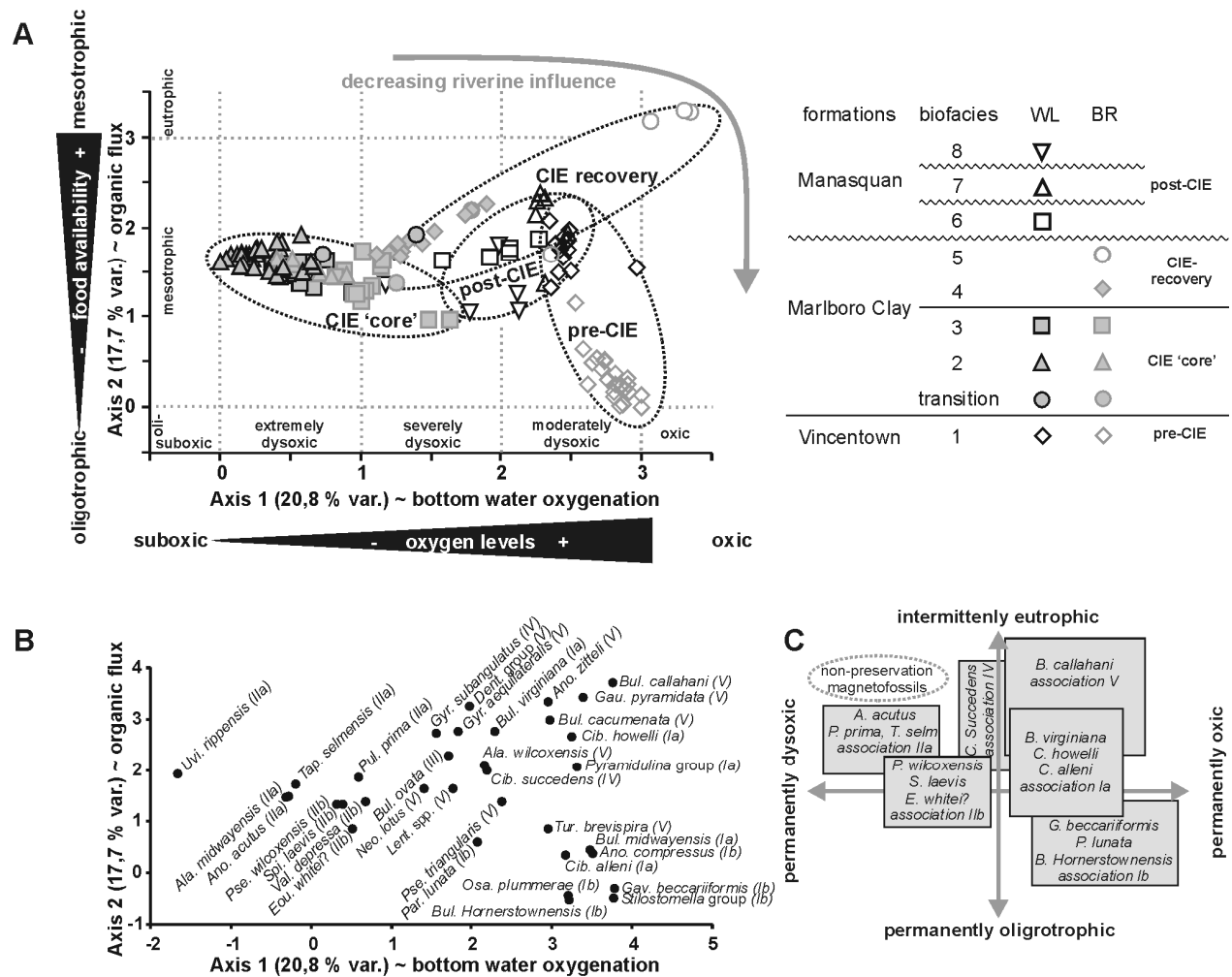


Figure 8

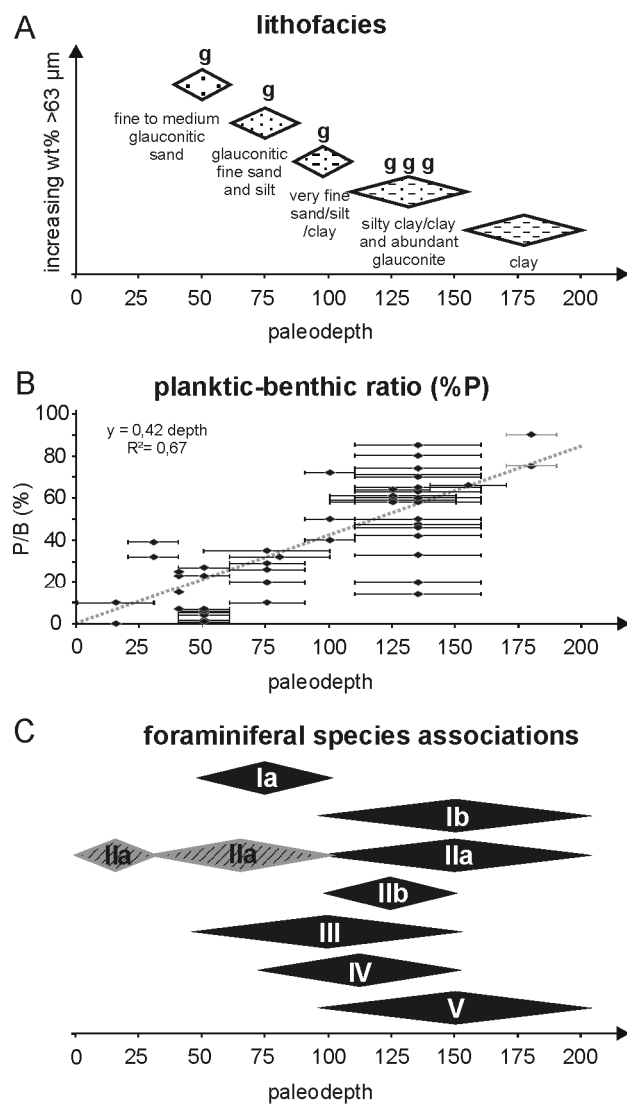


Figure 9

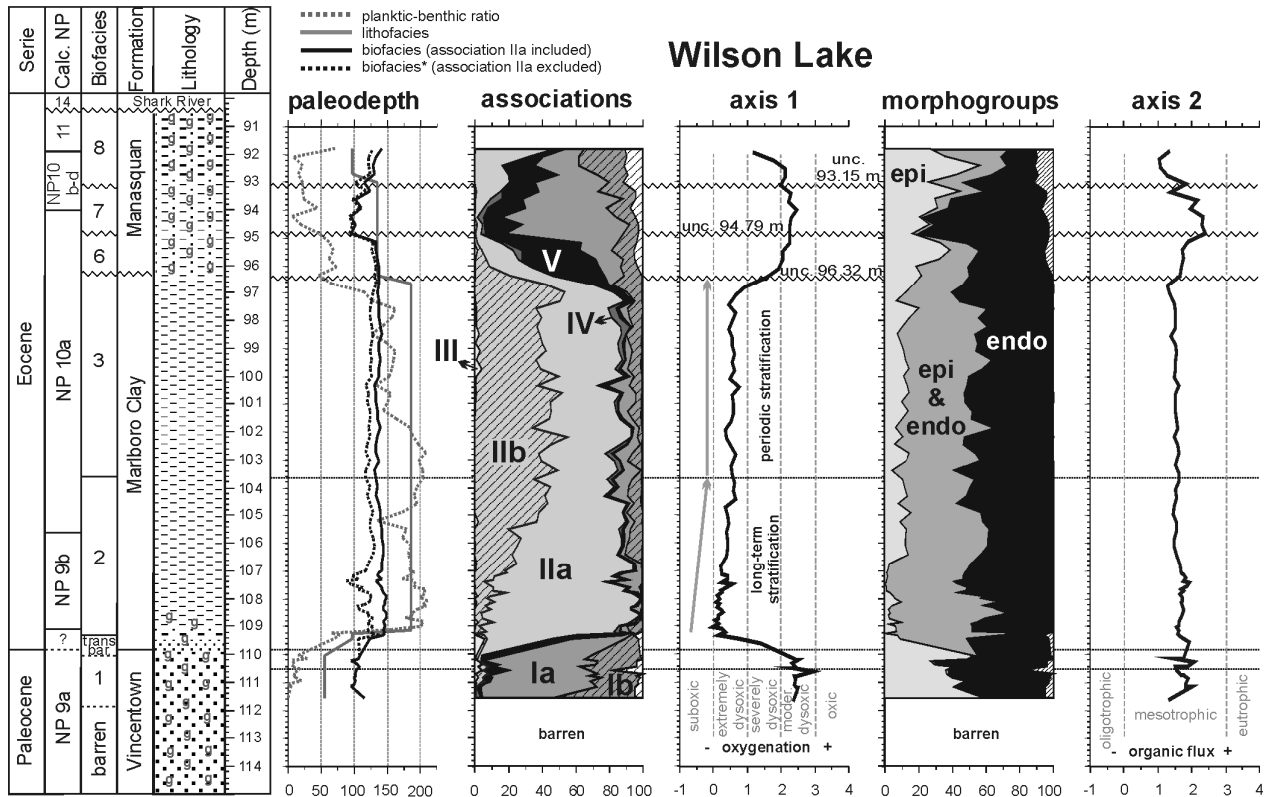


Figure 10

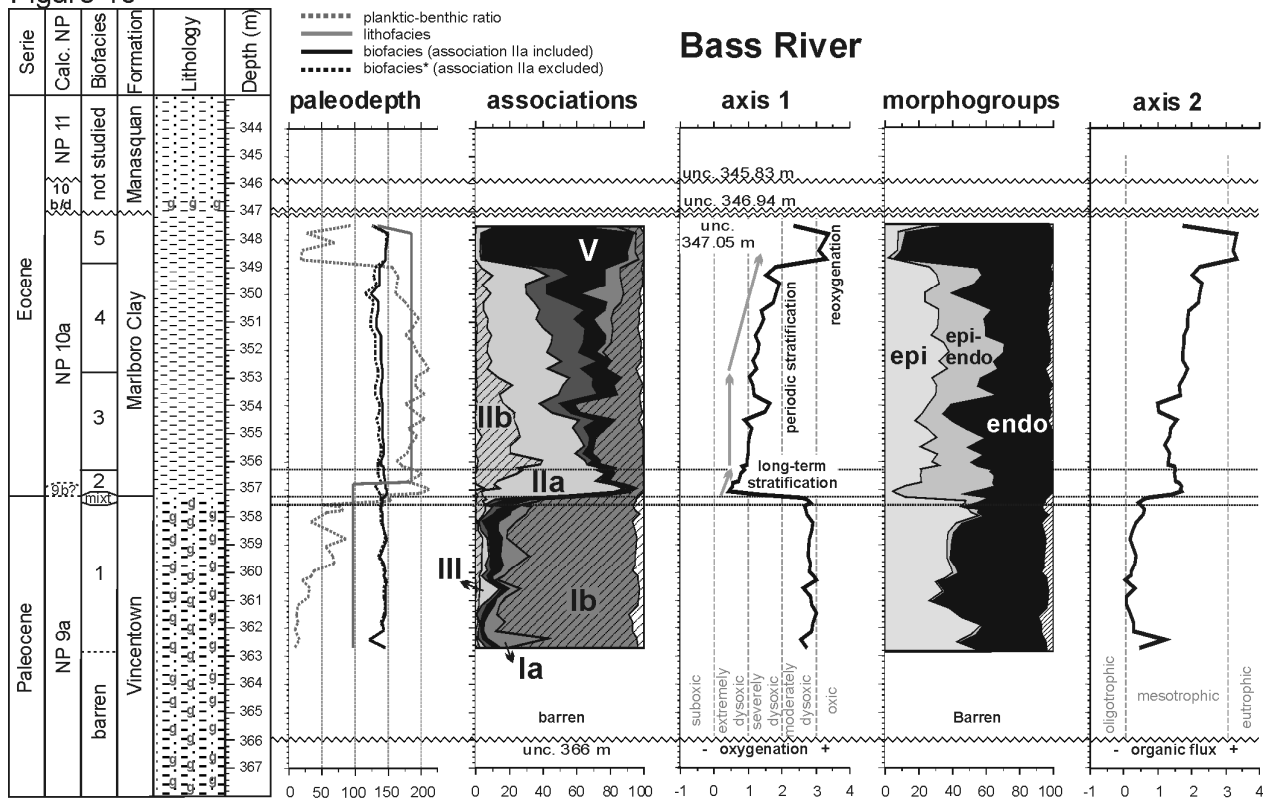


Figure 11

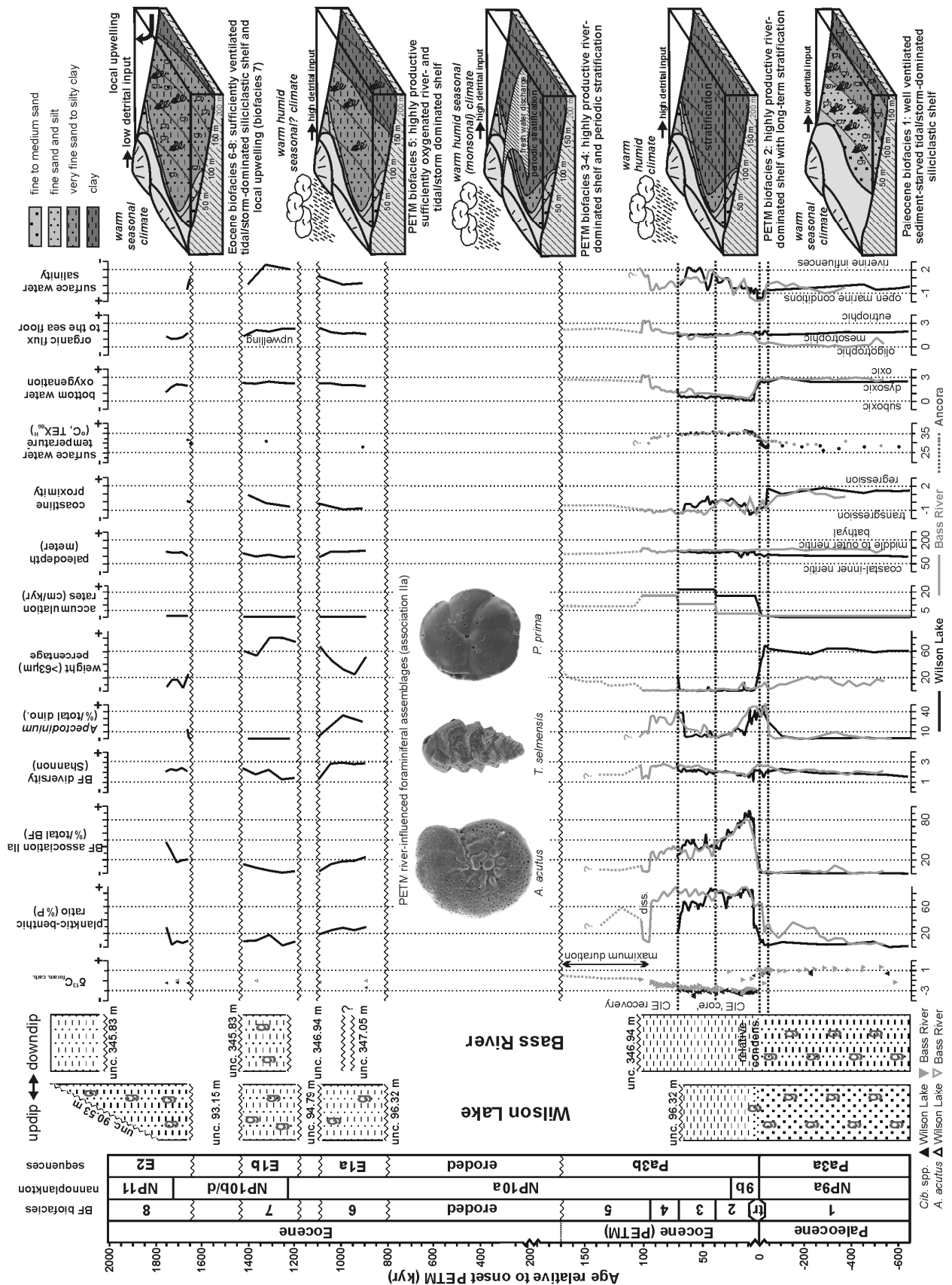
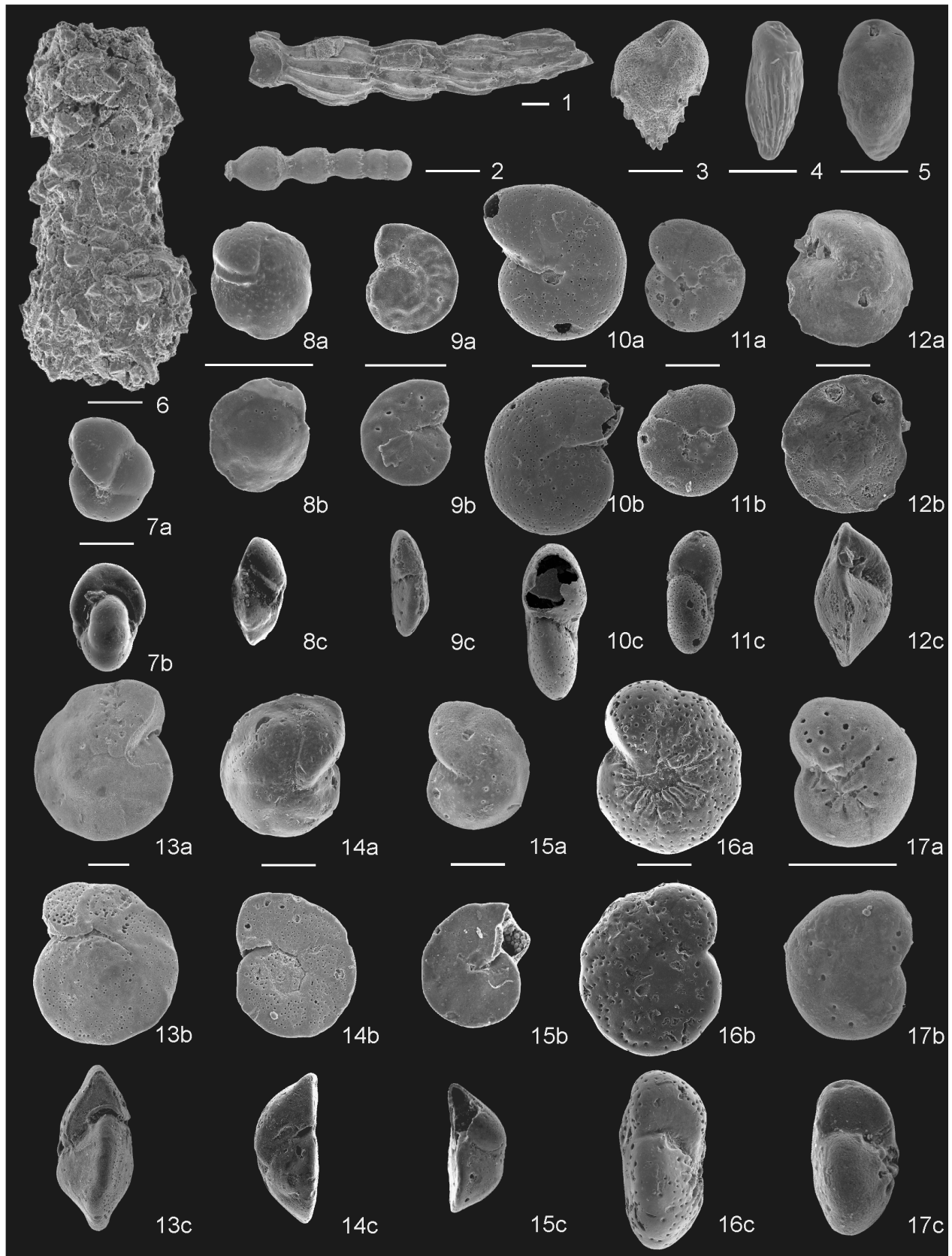
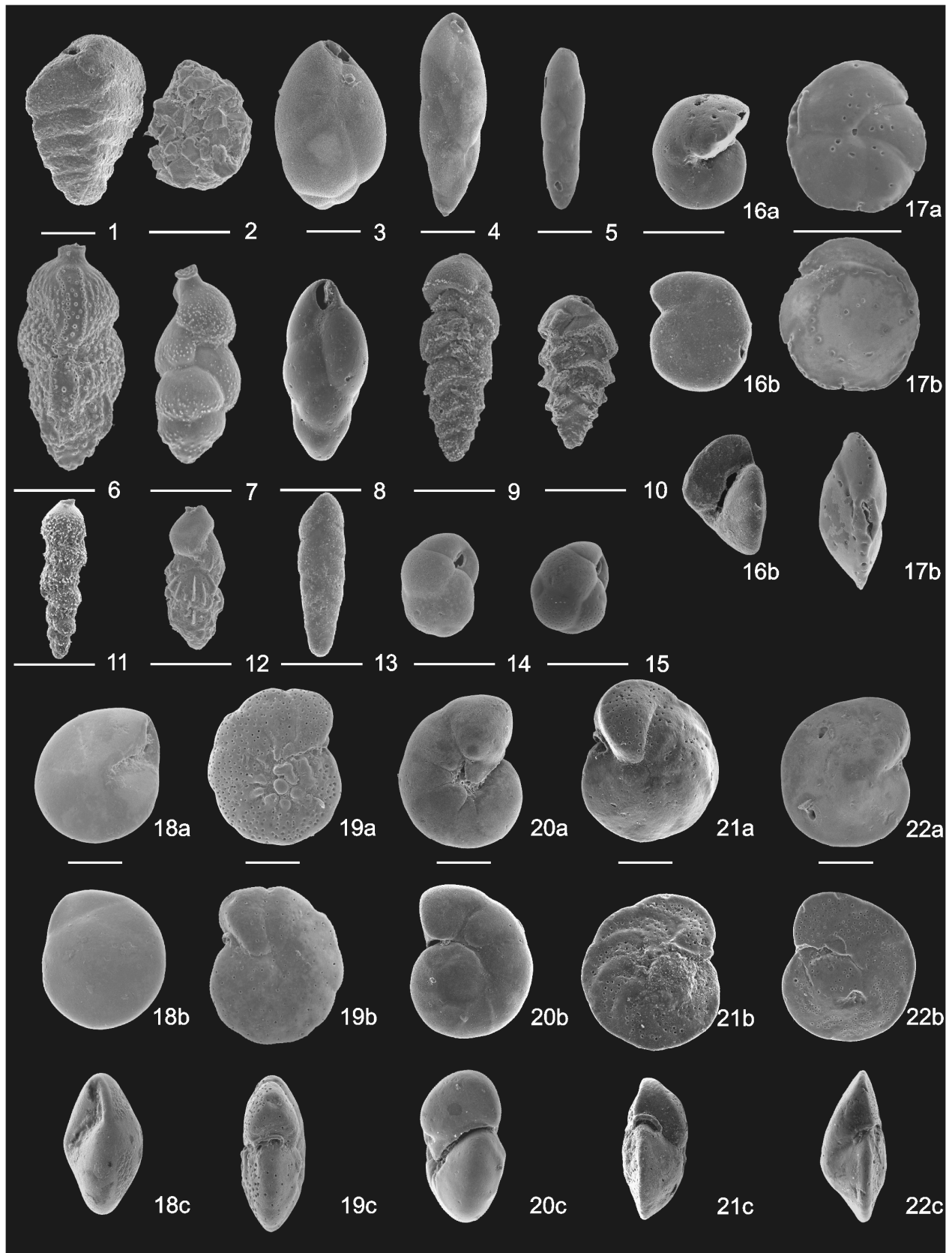
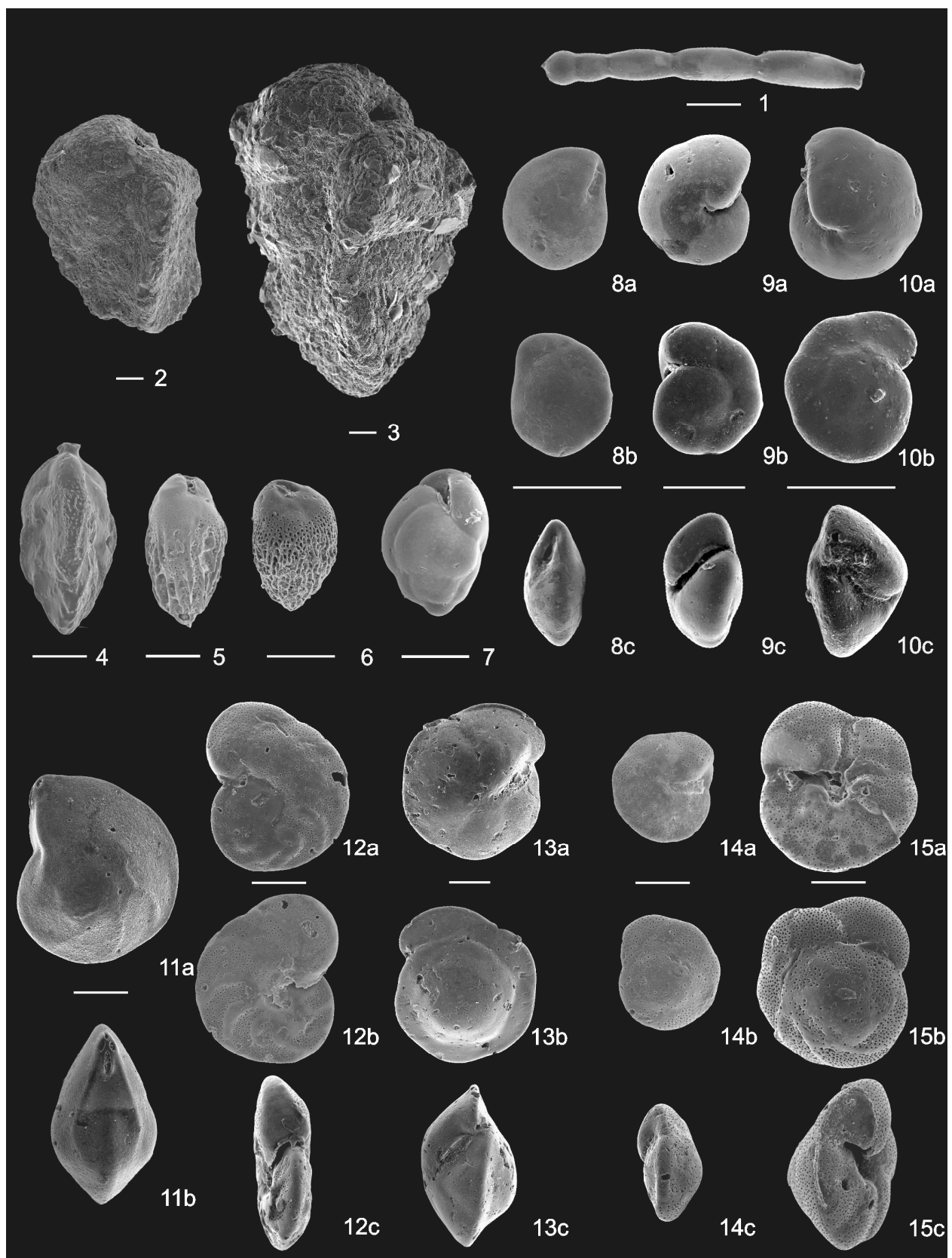


Figure 12







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